Course Information Page

Student Name:____

Student Email:____

Lab Room: **Lab Section:** **Weekday/Time:**

TA Name:____

Email:____

Office: **Office Hours:**

Course Lecturer:____

Email: ________________________________ **Office:** __________

Office Hours:

Lab Director: **Dr. Roger Haar**

Email: **haar@physics.arizona.edu** **Office:** **PAS 324**

Free tutoring: Consultation Room - PAS 372, Mon-Fri.

Administrative help: Academic Support Office - PAS 260

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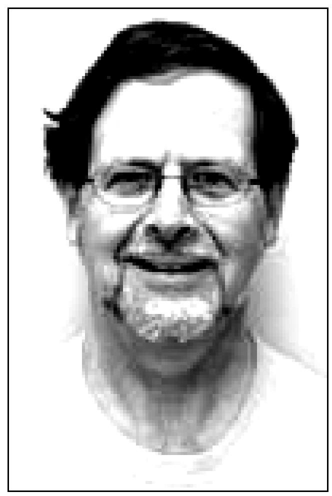
Introductory Electricity and Magnetism Laboratory Manual (2nd Edition)

By

R. Matt Leone, M.S., M.Ed., M.S.

Dr. Roger Haar, Ph.D.



June 2011
Based in part on previous
University of Arizona
Physics Department
Laboratory Manuals

Contents

Unit Summaries

Unit 1:

- Elementary Circuits
- Magnetism and Electrostatics

This unit emphasizes the concept of the *electrostatic potential (voltage)* and introduces the concept of *vector fields*. Students develop the practical skills of *wiring circuits* and using a *DMM*.

Unit 2:

- Electric Field Mapping
- Cathode Ray Tube

This unit emphasizes the concept of the *electric field* and its relation to *voltage*. Students continue to practice using the *DMM* and gain skills with *equipment needed to operate a CRT*.

Unit 3:

- Vulture Iguana Rabbit
- Oscilloscope

This unit emphasizes the concepts of *Ohm's law* and *oscillating voltages* (AC). Students begin developing the most important skill of *oscilloscope concepts and mastery*.

Unit 4:

- RC Circuits - DC Source
- RC Circuits - AC Source

This unit emphasizes the concepts of *differential equations* and *circuit capacitance*. Students practice the skill of *measuring a working circuit's properties with an oscilloscope*.

Unit 5:

- Motors
- Solenoids

This unit emphasizes the concepts of *induction* and *changing magnetic flux*. Students continue to practice *wiring* and *measuring multiple circuits with an oscilloscope*.

Unit 6:

- RLC Circuit - AC Driven
- RLC Radios

This unit emphasizes the concepts of *inductance, phase shifts and resonance*. Students continue to practice *wiring novel devices* and *measuring novel circuits with an oscilloscope*.

Tentative Lab Schedule

(Before printing the lab manual, replace this page with a **Tentative Lab Schedule** as two single-sided pages**.** Otherwise students should receive a tentative lab schedule as a handout or be able to view one online.)

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Physics 241 Lab Policies

(Before printing the lab manual, replace this page with the **Physics 241 Lab Policies** as three single-sided pages. Otherwise students should receive the Physics 241 Lab Policies as a handout or be able to view them online.)

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Strategies for Success

T**ake the lab activities seriously**, complete them conscientiously, discuss ideas fully with your lab partner, check answers with neighboring groups, discuss misconceptions with your teaching assistant (TA), etc.

After you have tried to figure some concept out and realize that you are stuck, **ask for help** from students around you, the TA, the lecturer, etc.

Form study groups and meet as often as possible. Be sure to be inclusive in creating your study groups.

Use the **free tutoring resources** available on campus especially the **Physics Department consultation room** (PAS 372, open weekdays).

How to Use this Manual

This manual has been written as if the author was standing beside you talking to you and asking probing questions. This manual often attempts to create a Socratic dialogue in written form to help students master difficult concepts.

The lab activities are often demanding and require the full amount of time allotted for the lab. **Be prepared when you arrive and do not waste time while you work**.

¿ - In this manual, **the upside down question mark is provided to indicate where the student must provide an answer**, explanation, numerical computation, table, graph, etc.

! - **Please read all warnings indicated by exclamation marks!**

TYPOS should be a nuisance only *once*. Please record any typos or poorly worded sentences and send them in an email so they can be fixed forever. Thank you bunches if you do this (Matt Leone, MattLeone@gmail.com).

Lab Report: General Guidelines

USE THE FOLLOWING SECTION TITLES AND LABEL THEM IN YOUR REPORT:

- **Title [0 points]** – A catchy title worth zero points so make it unique and fun.

- **Mini-Report [10 points]:** ***{3-5 paragraphs, 1-2 double-spaced pages}***
  Check each unit's grading guidelines to find which section to write about.
  Write a "mini-report" for one particular section of the lab manual. Describe what you did succinctly, and then what you found accurately. Then explain what the result means and how it relates to some of the concepts in the previous section. *You must write using sentences & paragraphs; bulleted lists are unacceptable.*
  - **Procedure:** Do not provide a lot of specific details, but rather you should summarize the procedure so that a student who took the course a few years ago would understand what you did.
  - **Results:** Provide a description of the data you obtained such as data tables. Restate any measured values, calculated slopes of lines-of-best-fit, etc. Do not *interpret* your results, save any interpretation for the discussion.
  - **Discussion:** Analyze and interpret the results you observed/measured in terms of some of the concepts and equations of this unit. It is all right to sound repetitive with other parts of the report.

- **Open-Ended Discussion [10 points]** – ***{1-2 paragraphs, ~1 page double-spaced}*** Choose one of the open-ended experiments from the two weekly activities to write about. Describe your experimental goal and the question you were trying to answer. Explain the ideas you came up with and what you tried. If your attempts were successful, explain your results. If your attempts resulted in failure, explain what went wrong and what you would do differently in the future. *You must write using sentences & paragraphs; bulleted lists are unacceptable.*

- **Graphs [5 points] - {attach to your typed report}** Graphs must be neatly hand-drawn <u>during lab</u> on graph paper. Your graphs must fill the entire page (requires planning ahead), include a descriptive title, labeled axes, numeric tic marks on the axes, and unit labels on the axes. If instructed to calculate the slope of the line-of-best-fit, write it directly on the graph.

- **Take-Home Quizzes [2x5 points = 10 points] - {attach after your Graphs}**

- **Selected Worksheet Pages [5 points] - {attach after your Take-Home Quizzes }**

Rules for Excused Absences

You should always email your TA as soon as you know that you will be missing a lab. You are not permitted to attend a different lab than the one for which you are registered. If you have a valid excuse <u>with</u> documentation, then you may complete the Makeup Lab near the end of the semester. Therefore, you may only makeup 1 lab at most.

If you are writing your biweekly lab report and you have been absent 1 week, then you may only earn 75% of the possible lab report points (30) out of the total possible (40). If you have a valid and documented excused absence, completing the makeup lab and writing the report for it will allow you to earn the remaining 10 points for the unit during which you were absent as earn the 5 points for the beginning-of-lab quiz that you were absent for.

When you are writing your biweekly lab report and you have been absent 1 week, then:

- **Write the Mini-Report using the section for which you were present.**
- **Write the Open-Ended Discussion using the open-ended activity for which you were present.**
- **Attach the graphs you created for the week you were present.**
- **Attach the Post-Lab Quiz for the week you were present.**
- **Attach the Selected Worksheet Pages you completed for the week you were present.**

For the makeup lab report, you will need to:

- **Write a Mini-Report.**
- **Do not write an Open-Ended.**
- **Attach the graphs you create for the makeup lab.**
- **Attach the Take-Home Quiz for the makeup lab.**
- **Attach *all* the Worksheet Pages you completed for the makeup lab.**

Unit 1 Lab Report Instructions

Unit Lab Report [40 points]

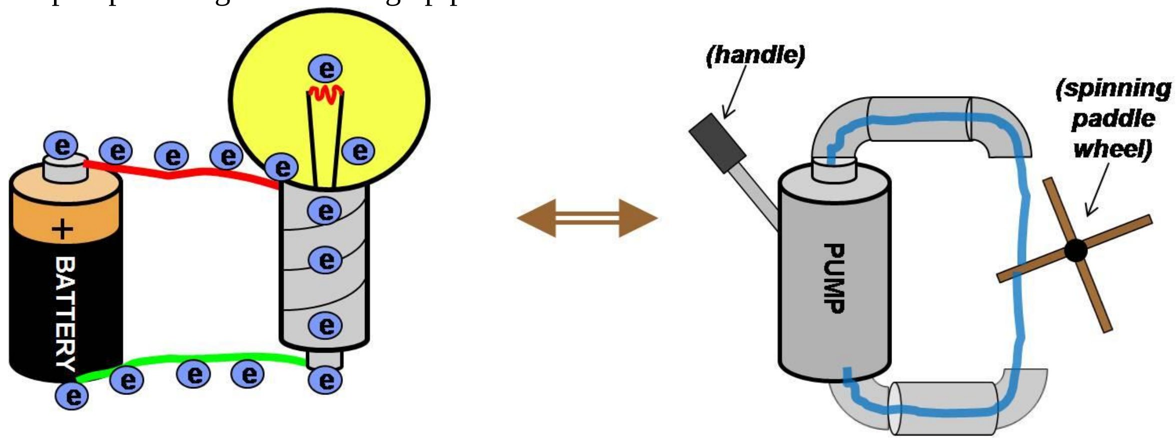
Use the following section titles in your report. Images, text or equations plagiarized from the internet are not allowed! Remember to write your report *alone* as collaborating with a lab partner will make you both guilty of plagiarism. **Please label your lab report sections:**

- **Title [0 points]** – A catchy title worth zero points so make it unique and fun.
- **Mini-Report [10 points]:** ***{4-6 paragraphs, ~2 double-spaced pages}***
  Choose **one** of the following sections about which to write your mini-report:
  Week 1 Section 4 or Week 2 Section 3
  Write a "mini-report" for one particular section of the lab manual. Describe what you did succinctly, and then what you found accurately. Then explain what the result means and how it relates to some of the concepts in the previous section. *You must write using sentences & paragraphs; bulleted lists are unacceptable.* ***Please label your mini-report sections:***
  - **Abstract:** Write 2-3 sentences about the goals of this section. Describe the concepts you were investigating and how the experimentation you performed allowed you to investigate these concepts. Write 2-3 sentences summarizing the procedure. Write 2-3 sentences summarizing the results and what the results mean with regard to the concepts you were investigating. *It is best to write the abstract last*.
  - **Procedure:** Do not provide a lot of specific details, but rather you should summarize the procedure so that a student who took the course a few years ago would understand what you did.
  - **Results:** Provide a description of the data you obtained such as data tables. Restate any measured values, calculated slopes of lines-of-best-fit, etc. Do not *interpret* your results, save any interpretation for the discussion.
  - **Discussion:** Analyze and interpret the results you observed/measured in terms of some of the concepts and equations of this unit. It is all right to sound repetitive with other parts of the report.
- **Open-Ended Discussion [10 points]** – ***{1-2 paragraphs, ~1 page double-spaced}***
  Choose **one** of the open-ended experiments from the two weekly activities to write about. Describe your experimental goal and the question you were trying to answer. Explain the ideas you came up with and what you tried. If your attempts were successful, explain your results. If your attempts resulted in failure, explain what went wrong and what you would do differently in the future. *You must write using sentences & paragraphs; bulleted lists are unacceptable.*
- **Graphs [5 points] - {attach to your typed report}** Graphs must be neatly hand-drawn <u>during lab</u> on graph paper. Your graphs must fill the entire page (requires planning ahead), include a descriptive title, labeled axes, numeric tic marks on the axes, and unit labels on the axes. If instructed to calculate the slope of the line-of-best-fit, write it directly on the graph.
  Week 1: none
  Week 2: none (so 5 points for free this unit!)
- **Take-Home Quizzes [2x5 points = 10 points] - {attach after your Graphs}**
- **Selected Worksheet Pages [5 points] - {attach after your Take-Home Quizzes }**
  Your TA will choose which pages you need to hand in.

Week 1 Pre-Lab: Elementary Circuits

Read the following short pre-lab upon which you will take a quiz at the beginning of lab.

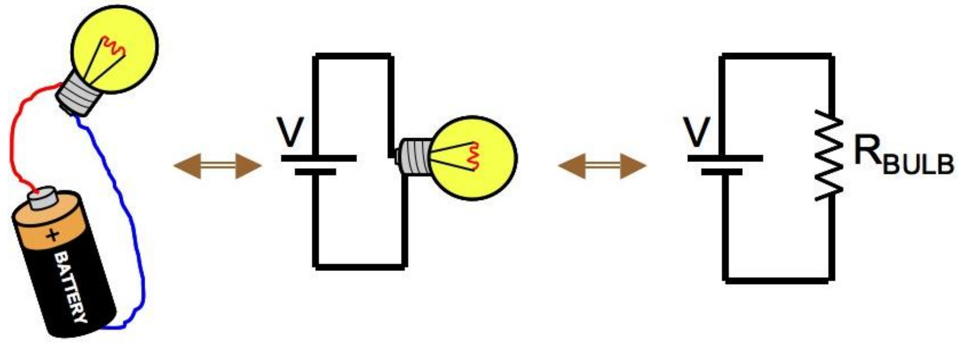
In a circuit, a battery pushes electrons along wires and through resistive components that absorb electrical potential energy. Voltage is a quantity that measures how much electrical potential energy each unit of charge is given as it moves through the circuit. The SI unit of voltage is the volt, which is written inside brackets in this manual: **[volts]** or **[V]**. The battery is like a pump moving water through pipes.



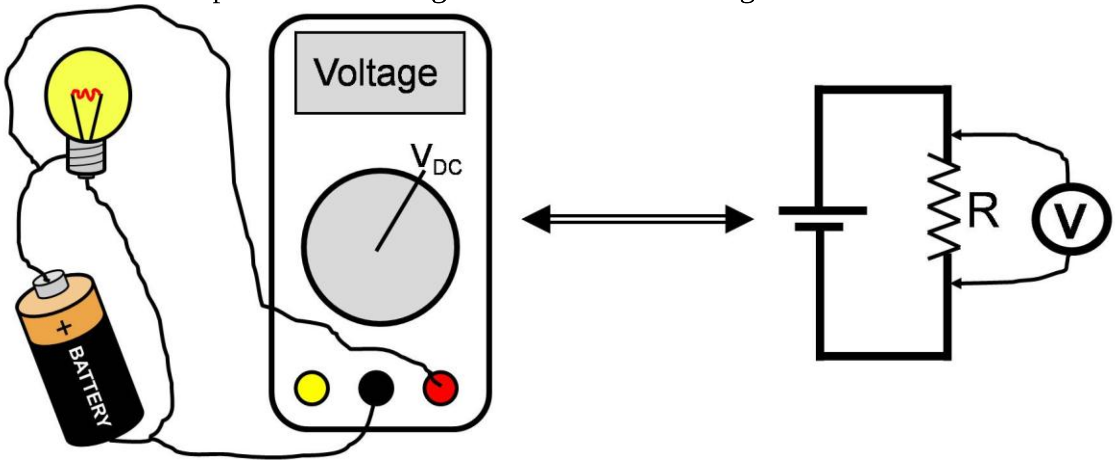
The current describes the amount of charge moving through the wires and components of the circuit in coulombs per second, which defines the SI unit **[ampere]** also written as **[amp]** or just **[A]**. Current is analogous to how much water is moving through a plumbing system. If a circuit is a single loop, then the current must be the same at any point in the circuit to prevent the accumulation of charge in part of the circuit. Of course, if a circuit branches into two wires, then the current will be divided between the two paths. These concepts explain why current cannot flow unless the circuit forms a loop so that electrons can get back to where they began.

The battery is expending energy and due to conservation of energy, this energy must be absorbed somewhere. The resistor is the circuit component that has 'electrical friction' which removes energy from the battery (a light bulb in the above picture). The SI unit that describes how much 'friction' the resistive component has is the **[ohm]** or **[Ω]**, where Ω is the capital Greek letter omega.

Circuit diagrams are simple ways to represent actual physical circuits. Below three unique pictures are shown to represent a certain battery-light bulb circuit, the third picture is called a **circuit diagram**. Note that the positive terminal of the battery is represented by a wider line than the negative terminal, and the resistive component (the bulb) is represented by zig-zag lines.

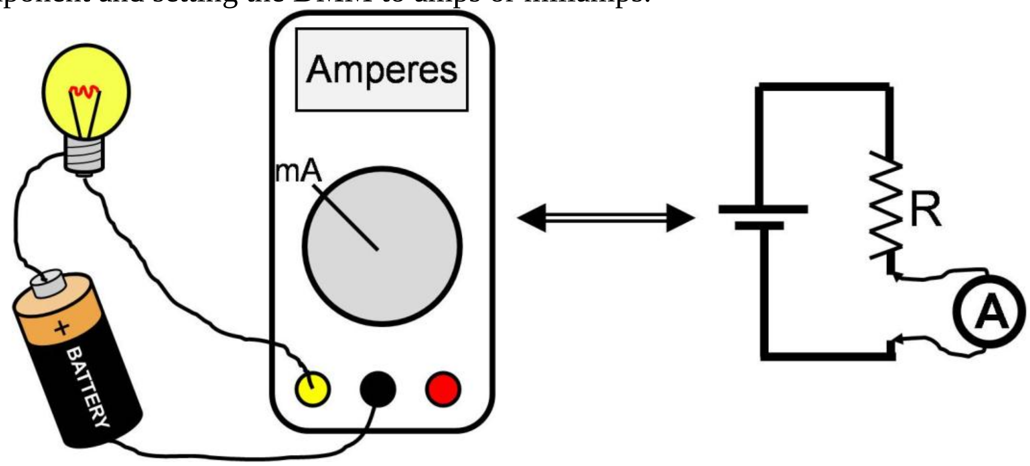


A **digital multimeter (DMM)** is a device used to measure voltage, current and resistance. A DMM may measure the voltage of a circuit component by applying its two leads in parallel on either side of the component and setting the DMM to DC voltage:

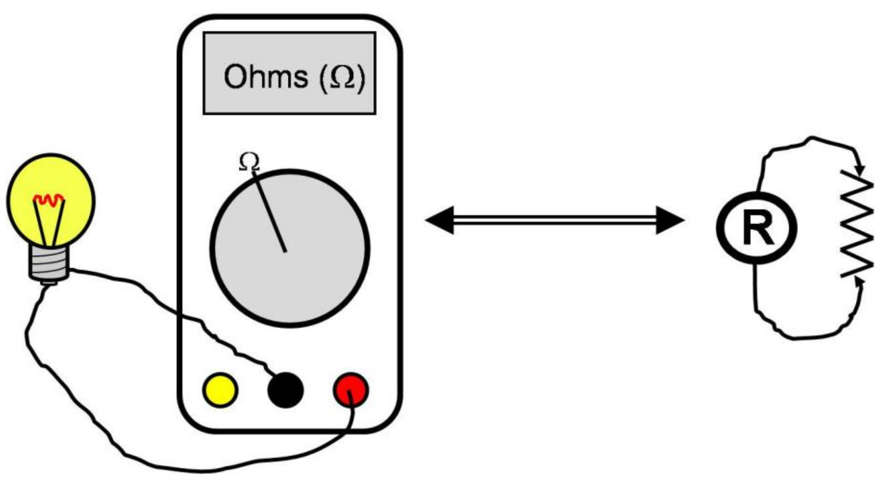


Note that most DMMs have three or more terminals for attaching leads even though you only use two at any given time. Your TA will help you choose the correct terminals.

A DMM may also measure the current through a component by being wired in series next to the component and setting the DMM to amps or miliamps.



A DMM can also measure the resistance of a component once it has been disconnected from the circuit:

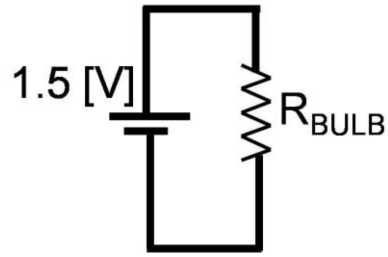


Week 1 Lab: Elementary Circuits

Students Absolutely Must Learn…

- To relate the concept of ‘voltage’ very closely with ‘electrical potential energy’ using “voltage height” diagrams.
- To think of current as marbles or water flowing in a garden hose and how current must be behave so as to prevent charges from piling up in any part of the circuit.
- To understand how components in parallel/series affect equivalent resistance.
- To understand how components in parallel/series affect current drawn from the battery.
- To understand how components in parallel/series affect the voltage delivered to a circuit component.
- To understand how the three previous concepts conspire to affect the power used by a component (as observed with bulb brightness).
- How to compare the currents and resistances of different circuits.
- To use a DMM to measure current, voltage and resistance (all have a different procedure!).
- To make a real circuit from viewing a circuit diagram.
- How to design and conduct an experiment to address an open-ended question.

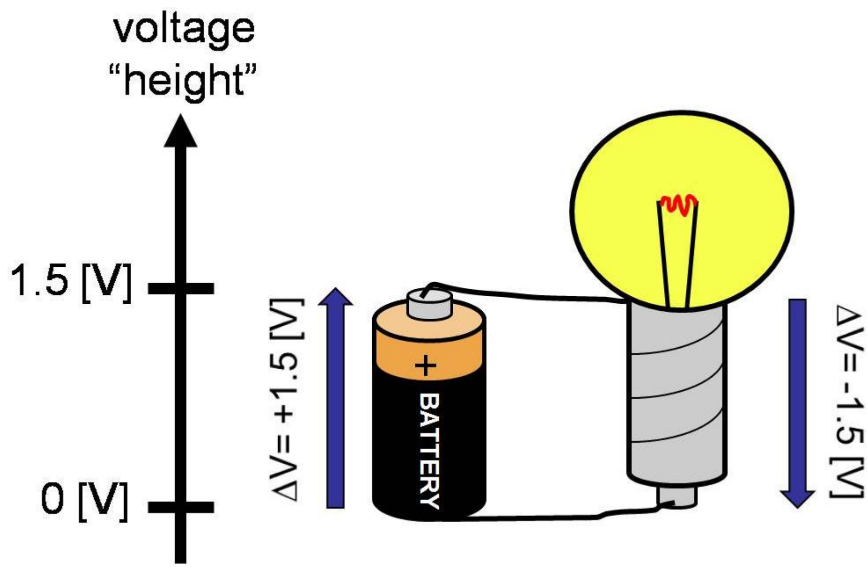
Section 1: thinking about voltage



The circuit diagram of a battery powering a light bulb is shown above. Introductory students sometimes confuse the new concepts of voltage, current, resistance, etc. Where voltage is concerned, a good way to think about what is happening is to think of voltage as a kind of height.

The battery "lifts" the electrons to a "height" of 1.5 [V] at the positive terminal of the battery. Then as the current flows through the light bulb, the electrons "fall" back to a "height" of 0 [V]. Current flows from high voltage to low voltage.

One could equivalently say that the electrical potential energy of the charge carriers is increased by the battery and then the charge carriers lose that potential energy as they flow through the light bulb.

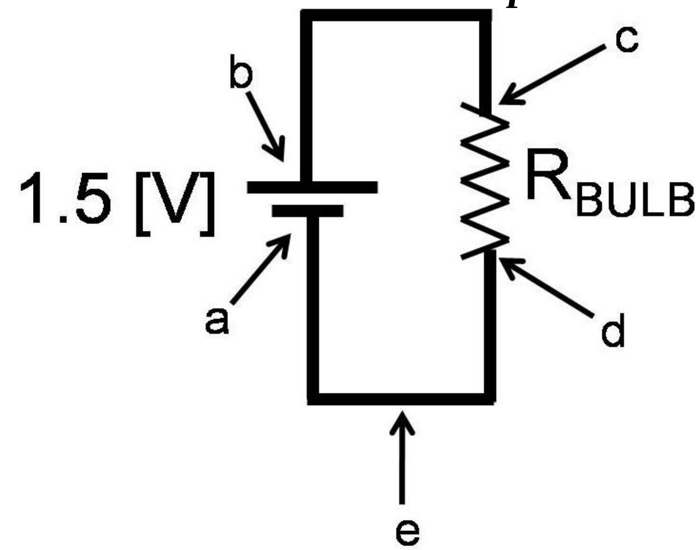


Note that the wires of the circuit are drawn nearly horizontal. This is because wires are highly conductive (very low resistance) and so there is no appreciable drop in electrical potential along a wire.

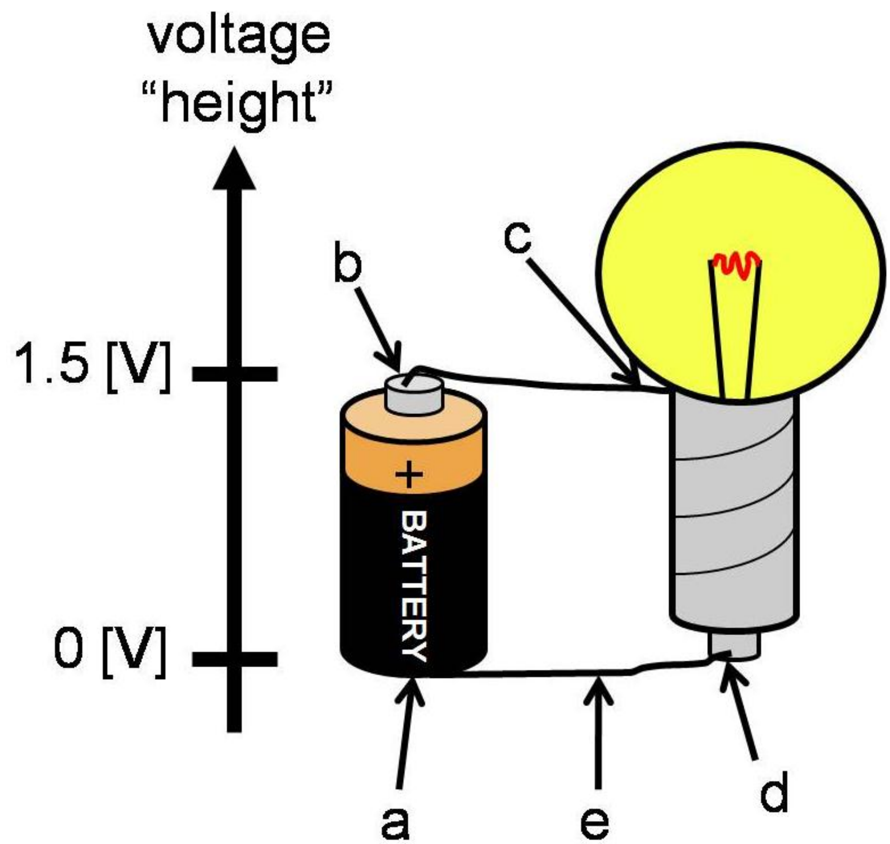
! Always use some resistance in your circuit when measuring amps or you will blow the fuse in your DMM.

The following pictures attempt to make this concept very clear by providing different ways to visualize the previous situation at various points of the circuit:

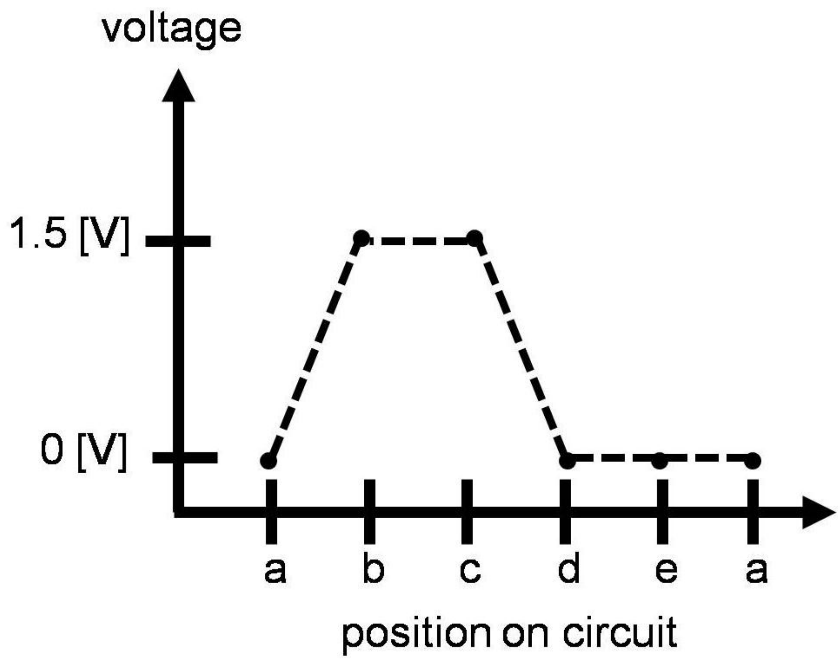
The circuit with labeled points:



Which one may think of using the following picture:



One can examine the change of voltage for the current moving from point to point through the circuit:



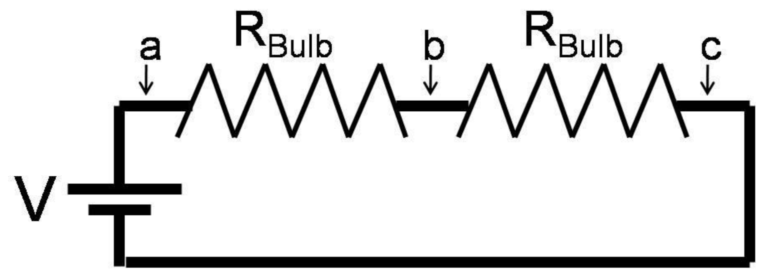
Examine the labeled points on the pictures above. Both pictures represent that same circuit labeled at the same points. Moving from point a to point b, the voltage increases by 1.5 [V], $V_{\text{a to b}} = +1.5\ [\text{V}]$. The DMM actually measures voltage *differences*. Placing the positive lead at 'b' and the ground lead at 'a' would give the measurement: $V_{\text{a to b}} = V_b - V_a = +1.5\ [\text{V}]$.

Points b and c are at the same voltage "height". Therefore, $V_{\text{b to c}} = 0\ [\text{V}]$. As the current travels through the light bulb, the voltage decreases from 1.5 [V] to 0 [V] so that $V_{\text{c to d}} = -1.5\ [\text{V}]$. Points d and e are at the same voltage height so there is no voltage change between them. If you put the positive lead of the DMM at point b and the negative lead at point d, the DMM display would show a voltage of $V_{\text{d to b}} = +1.5\ [\text{V}]$.

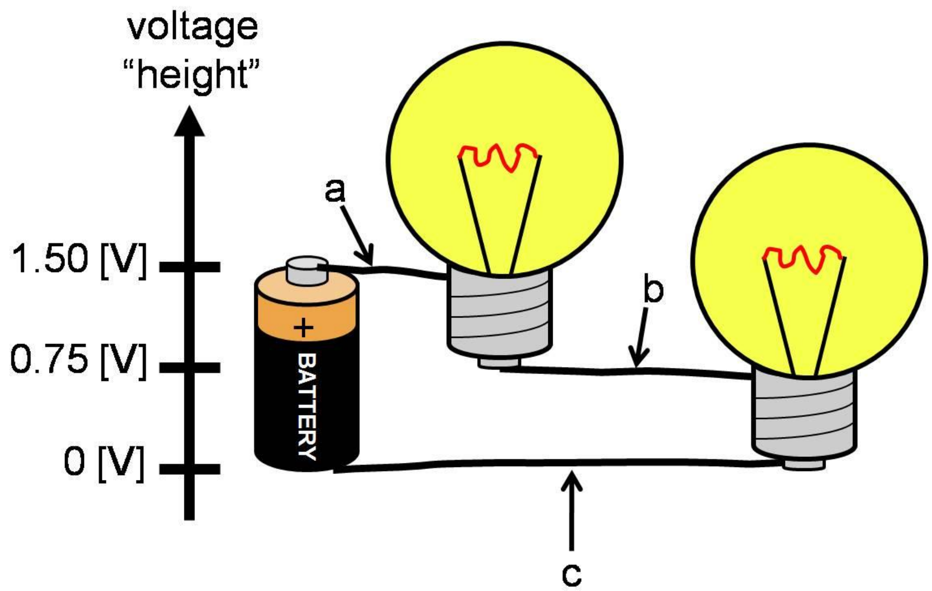
¿ 1-1

For the previous circuit, if you put the positive lead of the DMM at point e and the negative lead at point c, what value would the DMM display? {Hint: what is $V_{\text{c to e}}$?} ***Introductory students are often confused by negative DMM readings. The negative lead is the starting point and the positive is the final, the DMM tells the voltage going from negative lead to positive.***

Now imagine adding another identical light bulb in series with the first as shown in the following picture. Charge flowing through this circuit will lose half of its electrical potential energy traversing the first light bulb and the other half of its electrical potential energy traversing the second light bulb:



Which one may think of using the following picture:

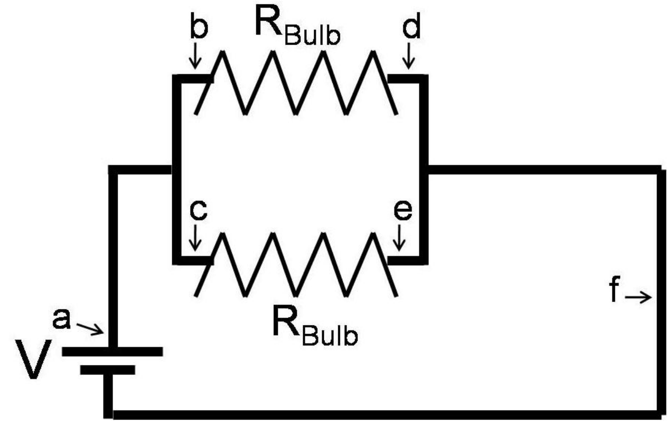


As the current travels from the voltage source at a through the first bulb to b, the voltage drops 0.75 [V], and from b to c the voltage drops again by 0.75 [V]. A DMM would measure the voltage of either light bulb as 0.75 [V].

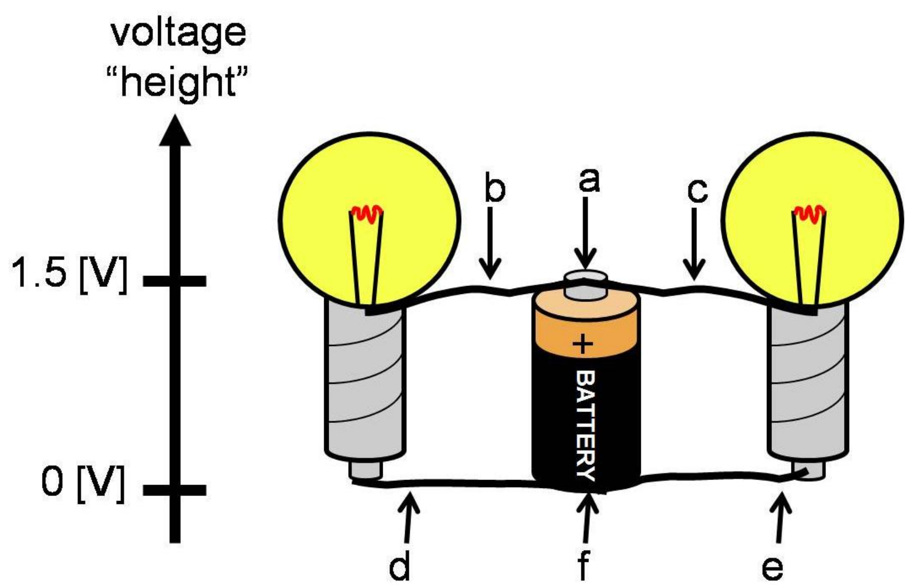
¿ 1-2

If a 6 [V] battery had been used instead of a 1.5 [V] battery, what would the voltage drop across a single light bulb be?

Now imagine adding the extra identical light bulb in parallel with the first (shown in the following figure). Charge flowing through this circuit will lose all of its electrical potential energy if it follows the path to the left or all of its electrical potential energy if it follows the path to the right. The moving charge cannot flow through both bulbs simultaneously so half the current must go one way and half the other.



Which one may think of using the following picture:



The current leaves the battery with 1.5 [V] and takes one of two paths through a light bulb in which the voltage drops to 0 [V]. A DMM would measure the voltage of either light bulb as 1.5 [V].

¿ 1-3

If a 6 [V] battery had been used instead of a 1.5 [V] battery, what would the voltage drop across a single light bulb be?

Section 2: circuit basics

Remember that you measure voltage by using two DMM leads and placing the DMM in parallel with the component you are measuring.

! Be sure your DMM is set to measure *DC voltage* so that the internal circuit of the DMM provides an enormous resistance. Otherwise you may blow a DMM fuse (or worse).

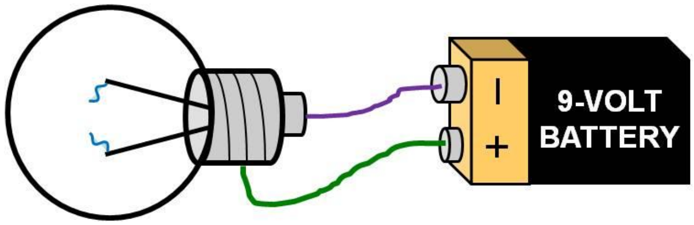
¿ 2-1

Use your DMM to *quickly* measure the voltages of the following batteries (if available): D-cell, AA-cell, AAA-cell, C-cell, 9-volt, 6-volt. Measure the voltage of two 1.5 [volt] batteries in series. Measure the voltage of two 1.5 [volt] batteries in parallel. Make a short table of your results below:

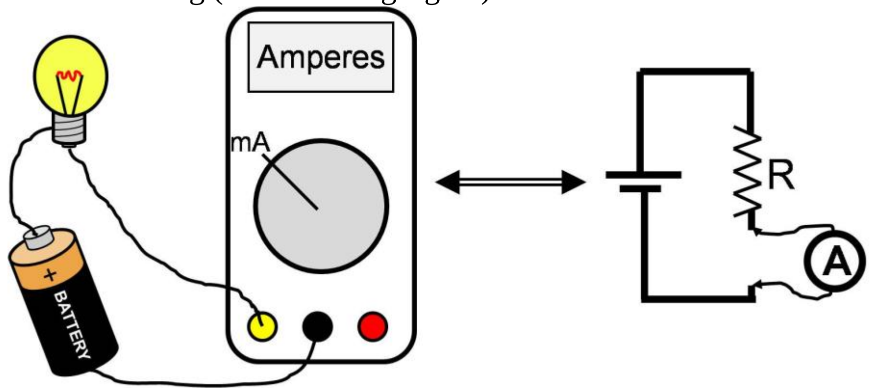
¿ 2-2

If you measure the voltage of a battery to be +1.5 [V], then switching the DMM leads will cause you to measure -1.5 [V]. Explain why this happens using the concept that a voltmeter is a "voltage subtraction machine".

! Too much electrical potential energy in the charge carriers can melt the tungsten filament of a bulb:



Measure current by using **one** DMM lead and placing the DMM in series next to the component you are measuring (see following figure).



! **When you are not sure how large the current may be, always use the DMM on the large current setting (large fuse), then switch to the small current setting if appropriate (small fuse).**

¿ 2-3

Measure the current through a single small incandescent light bulb powered by a 1.5 [V] battery. Check your result with another group's to be sure that your DMM measures current correctly. Write your measured current in SI units. Note that many times in lab you may only need to describe the magnitude of a current while on a lecture exam you usually need to describe its direction as well.

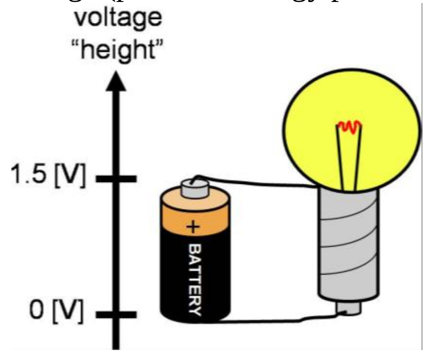
¿ 2-4

Measure the resistance of a single, cold unpowered light bulb. This is not a useful observation since a light bulb is non-ohmic: it's resistance changes when used in a circuit (its resistance grows with increasing temperature). Write your measured resistance in SI units.

¿ 2-5

Measure the resistance of your finger (from tip to base) and write the result in SI units. Compare your measurements to those of other students. Explain what might account for such a wide range of varying finger resistances?

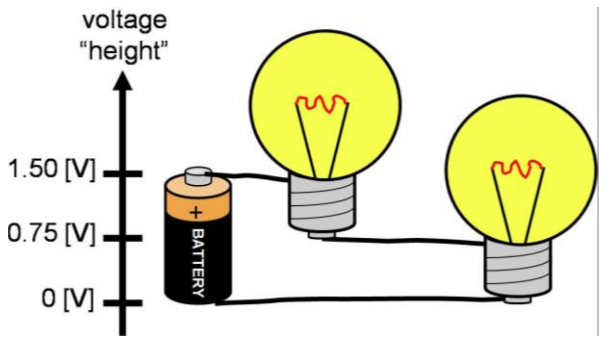
One way of thinking about a circuit with constant current is to use a sort of voltage "height" diagram. The y-axis represents voltage (potential energy per unit positive charge).



¿ 2-6

Experimentally verify that the voltage supplied by the battery is equal and opposite to the voltage drop across the light bulb. What fundamental physical law assures that this happens? Hint: what is a fundamental conserved quantity in physics? (Using the previous figure.)

Now examine two light bulbs in series:

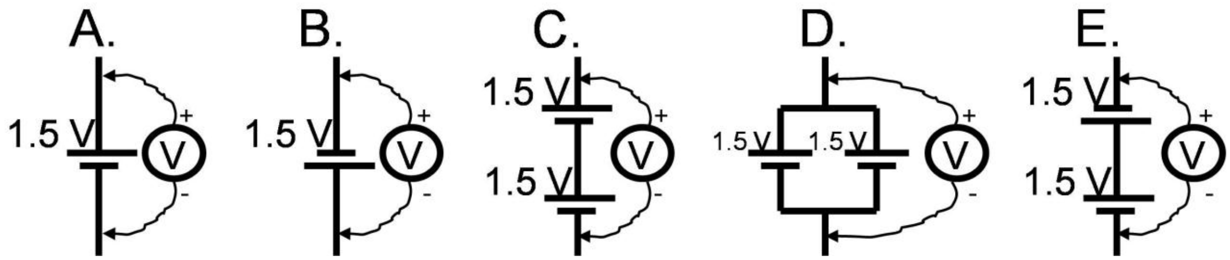


¿ 2-7

Experimentally verify that the ΔV supplied by the battery is equal to the sum of the ΔV's across each light bulb. Then experimentally verify that the current leaving the battery is the same as the current in the first bulb is the same as the current in the second bulb. Finally, measure the resistance of two separate single cold bulbs, and then measure their total resistance when placed in series. Record your results and check with neighbors. (Using the previous figure.)

Section 3: circuit behavior

In this section, you will make predictions about different circuits, then build and test them. Always use SI units.

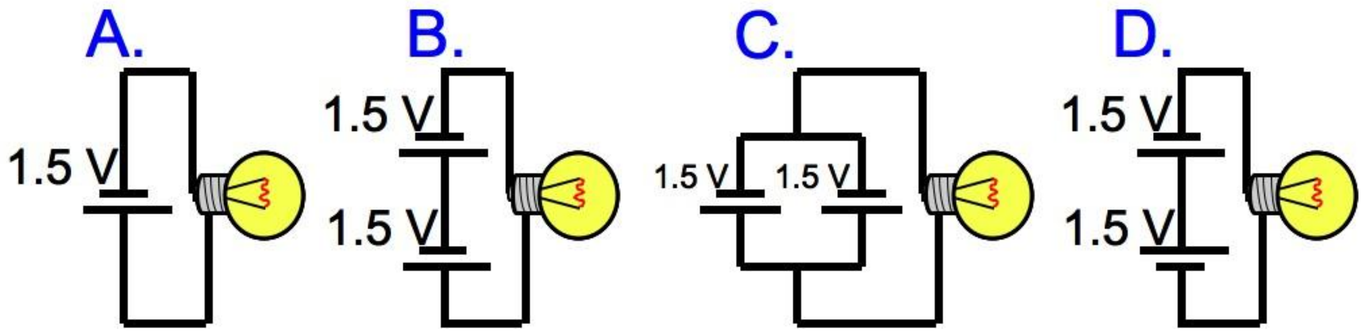


¿ 3-1

For the previous figure showing various arrangements of batteries, predict the voltages that would be measured. Explain your predictions. (Write *both* your predictions and explanations.)

¿ 3-2

Now set up each of the circuits and test your predictions. What are the actual voltages of the battery arrangements? Be sure to apply the positive and negative leads of your DMM correctly (as indicated) to obtain the correct sign of the voltage (compare the sign of the voltage in circuits a and b). If some of your predictions are wrong, ask around and figure out why, then explain why you were mistaken.



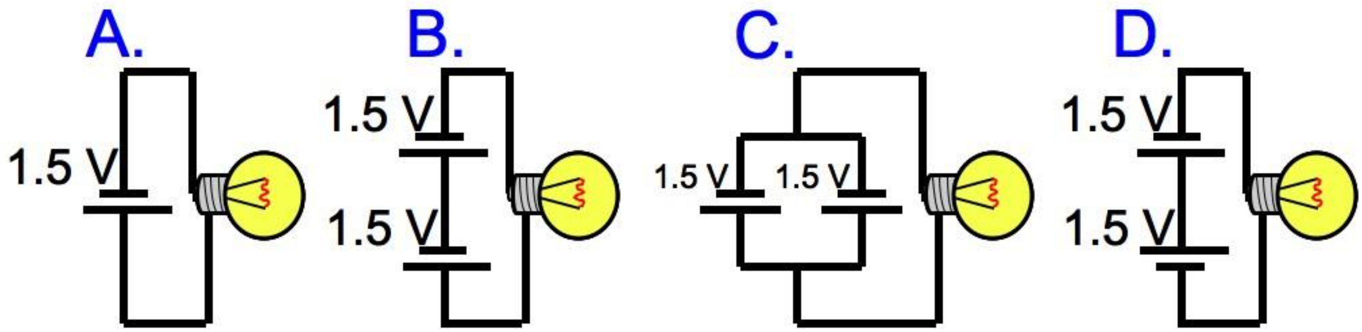
¿ **3-3**

For the previous figure, predict the order of brightness of the bulbs from least to most bright and then explain why you think this will be the case. (Write *both* your predictions and explanations.)

! **Always make the circuit first before you approach it with your DMM.**

¿ **3-4**

Now set up each of the above circuits and test your predictions. What is the actual order of the bulbs from least to most bright? If some of your predictions are wrong, ask around and figure out why, then explain why you were mistaken.



¿ 3-5

For the previous figure, predict the order of the magnitude of current through the light bulb from least to greatest and then explain why you think this will be the case. (Write *both* your predictions and explanations.)

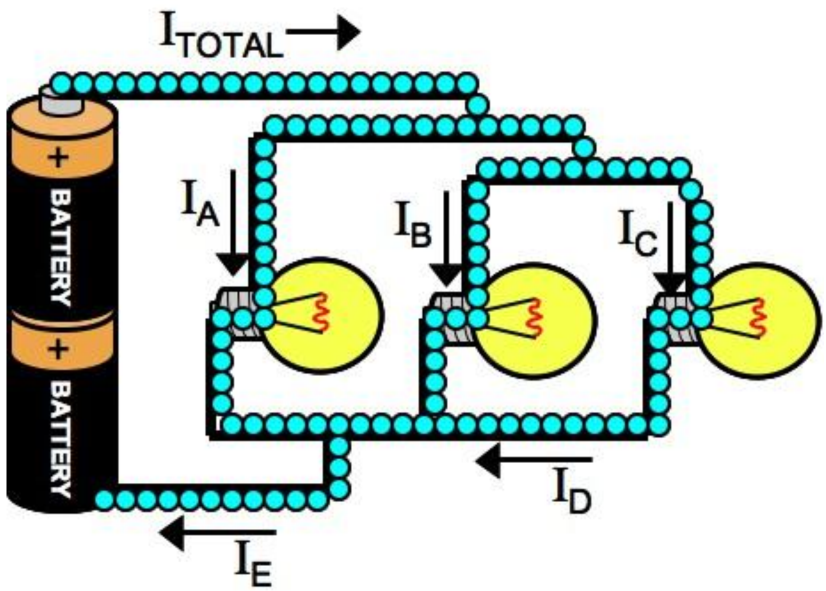
¿ 3-6

Now set up each of the above circuits and test your predictions. What is the actual order of the magnitude of bulb current from least to most? If some of your predictions are wrong, ask around and figure out why, then explain why you were mistaken.

Section 4: more circuit behavior

The following circuit uses two 1.5 [V] batteries in series to power three identical light bulbs. Marbles are shown to represent the unit charge carriers that produce the current in the circuit. Thus each marble represents 1 [coul].

For every second of time that passes, 9 marbles flow from the top of the battery so we say that I_{TOTAL}= 9 [amp]. The marbles are pushed through the circuit by the battery and must push each other out of the way to proceed through the. The marbles must return to the bottom of the batteries to replenish the batteries' reservoir.



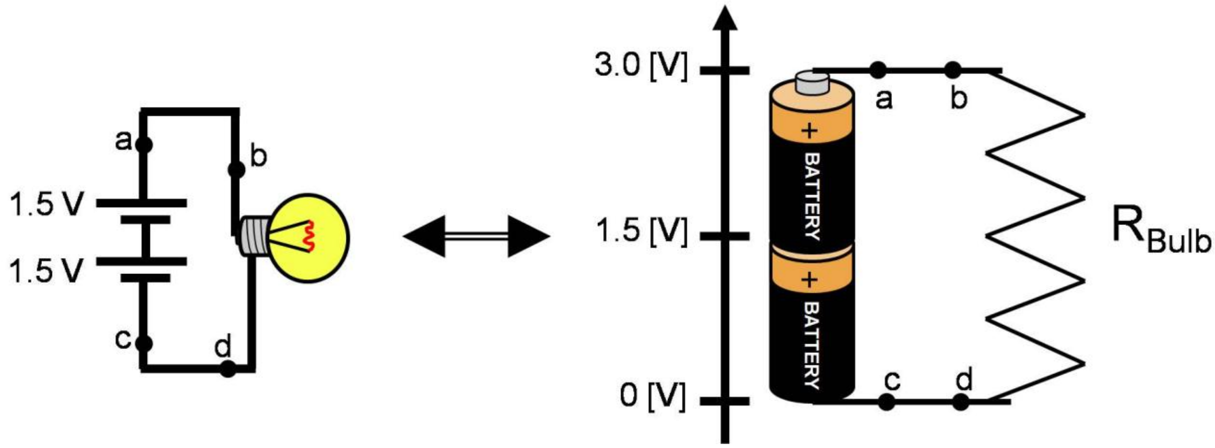
¿ 4-1

Calculate the current of marbles for each of the five delineated parts of the wire (I_A, I_B, I_C, I_D, I_E).

¿ 4-2

Explain what is meant when an electrical engineer says that they will lower the total resistance of a circuit by adding a component in parallel.

In the following simple circuit, four locations along the circuit's wires are labeled.



¿ 4-3

If the negative lead of your DMM was placed at location d, *predict* what the voltage readings would be on the DMM screen if the positive lead was placed at each other location in turn. Be sure to include the sign of the electric potential (voltage difference). Your predictions in SI units:

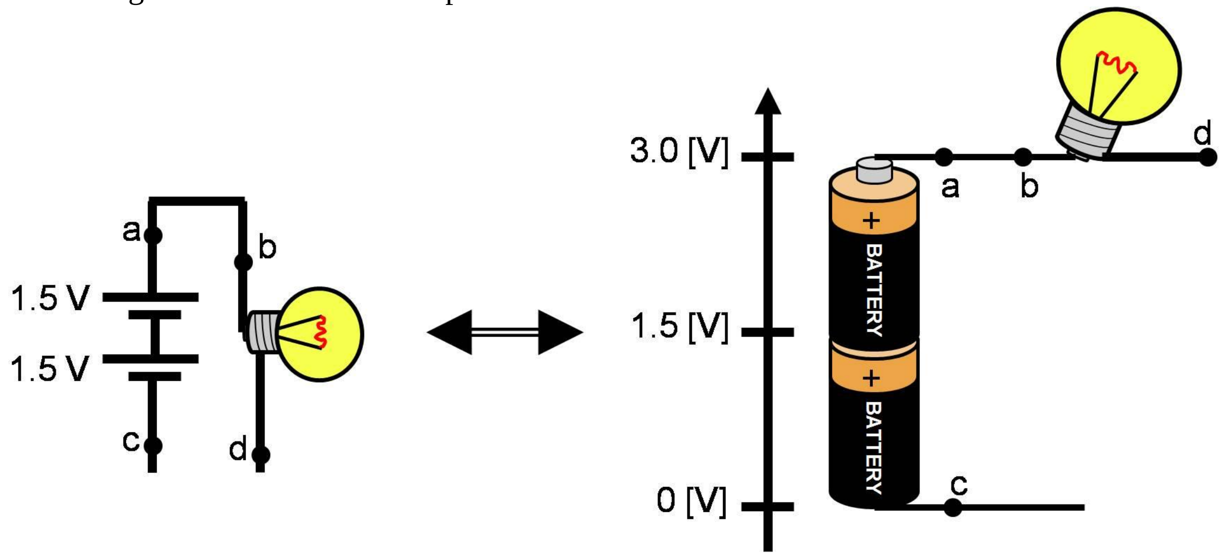
¿ 4-4

If the negative lead (common ground) of your DMM was placed at location a, *predict* what the voltage readings would be on the DMM screen if the positive lead was placed at each other locations in turn. Be sure to include the sign of the electric potential (voltage difference). Your predictions in SI units:

¿ 4-5

Now set this circuit up and test your predictions. Record each of your results and if some of your predictions were wrong, explain the mental misconceptions you held. Your observations in SI units and any explanations of misconceptions:

Now imagine the circuit from the previous subsection with a section of wire removed.



¿ 4-6

If the grounding lead of your DMM was placed at location d, *predict* what the voltage readings would be on the DMM screen if the positive lead was placed at each other location in turn. Be sure to include the sign of the electric potential (voltage difference). Your predictions in SI units:

¿ 4-7

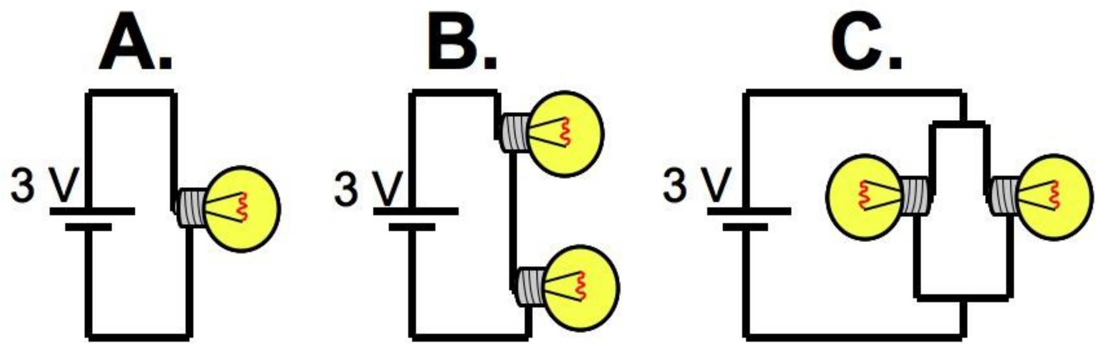
Now set this circuit up and test your predictions. Record each of your results and if some of your predictions were wrong, explain the mental misconceptions you held. Your observations in SI units and any explanations of misconceptions:

¿ 4-8

Why doesn't placing the DMM between points c and d complete the circuit and cause current to flow thus lighting the bulb? Hint: there may be *some* current flowing, but…

Section 5: comparing circuit behaviors

Below are three light bulb configurations made with identical bulbs. Imagine that each light bulb carries 1 [Ω] of resistance regardless of its temperature (unrealistic). Answer all the following questions without making observations. Note: drawing energy-circuit diagrams like those of the previous section is sometimes helpful.



¿ 5-1

Calculate the total resistance (equivalent resistance) for each circuit. Your answers in SI units. You don't need any fancy equations to do this so long as you remember that to push the electrons through twice as many resistors requires more "effort" while providing the electrons twice as many paths reduces the "effort" needed.

¿ 5-2

Calculate the voltage across each light bulb. Your answers in SI units:

¿ 5-3

If circuit A is known to produce 3 [A] of current through the battery, find the currents through the batteries in circuits B and C. Your answers in SI units:

¿ 5-4

Use your previous answer to find the current through each single light bulb in the three circuits. Your answers in SI units:

The **power supplied** by the battery is equal to the current emanating from the battery times the voltage of the battery, $P_{\text{supplied}} = I_{\text{battery}} \cdot V_{\text{battery}}$. The **power dissipated** by a resistive circuit component is found by multiplying the voltage drop across the component and the current flowing through the component, $P_{\text{dissipated}} = I_{\text{component}} \cdot V_{\text{component}}$. The SI unit of power is **[watts] or [W]**. If you have ever imbibed the soft drink *Mr. Pibb* then you can remember the power formula by thinking of *Mr. PIV*.

¿ 5-5

Use your previous answers to find the power dissipated as heat and light by each light bulb in the three circuits. Your answers in SI units:

¿ 5-6

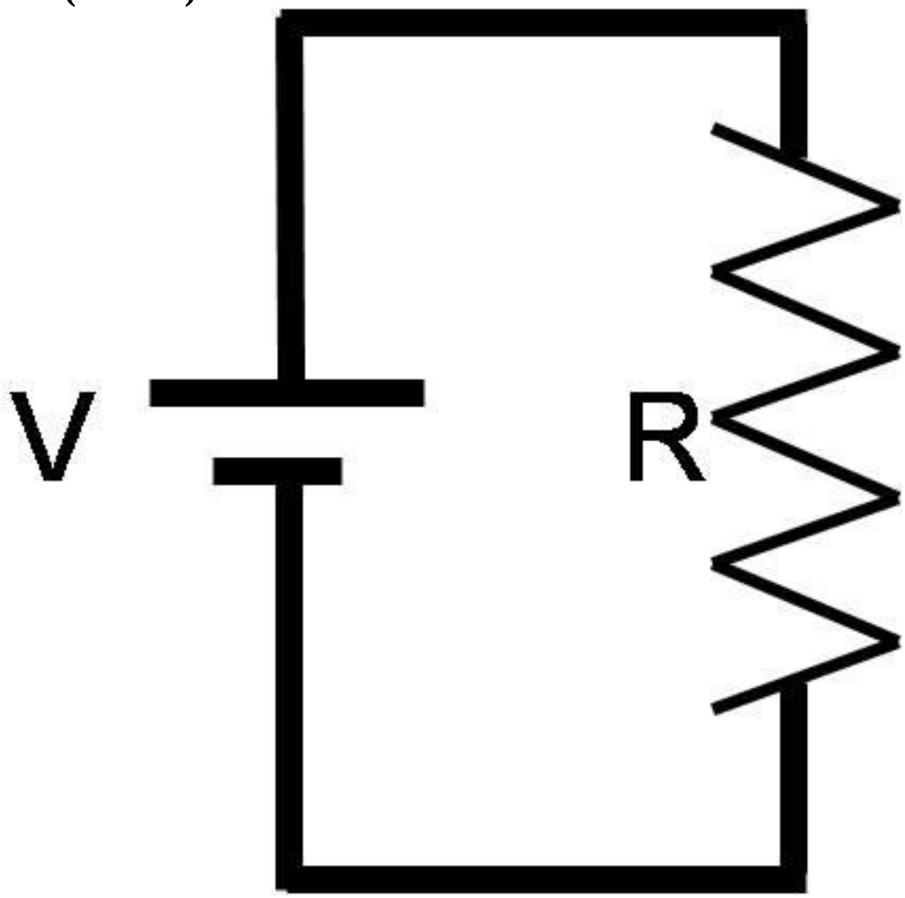
Use your previous answer to compare the brightness of each light bulb in the three circuits. Your answers:

¿ 5-7

Finally, use your previous answers to calculate the total power output by the batteries in each circuit. Your answers in SI units:

¿ 5-8

An electric field always points from high voltages toward low voltages. Electrons are negatively charged and so flow from low to high voltages. In the following circuit diagram, draw the direction of the electric filed inside the resistor (label it) and then draw the direction the electron moves through the resistor (label it).



Electrons are negatively charged so flow in the opposite direction of the defined current. Your answer to the previous questions should show the electrons moving in the opposite direction from the electric field. The defined current would be in the same direction as the electric field.

Section 6: authentic assessment

A popular video shown to education majors has an interviewer approaching students during graduation at Harvard and MIT. The interviewer provides a light bulb, a single wire and a battery. Very many of the graduates could not make the bulb light! (They were most likely *not* engineering majors.) This video is supposed to teach teachers that simple concepts can be misunderstood despite expensive training.

Not on our watch! You never know where these video makers might come next so we must be prepared. Use a single wire, a 1.5 [V] battery and a small bulb, and make the bulb light up.

If you are uncomfortable having another student check your work, please ask your TA.

¿ 6-1

Show a student in a different group that you can successfully light a bulb with a wire and a battery. Once you are successful and have them sign below. Note: if someone is stuck, please give them advice!

"Yes, I have seen this student light a bulb. They are well-prepared for surprise interviews!"

Student Signature:____

Section 7: open-ended

Listed below are several formulae for finding a total resistance for two resistors combined in parallel. Most of these formulae are wrong. You need to find the correct formula (or formulae) for the total resistance of two resistors combined in parallel.

A. $R_{\text{total}} = R_1 \times R_2$

B. $R_{\text{total}} = R_1 + R_2$

C. $R_{\text{total}} = \dfrac{R_1 \times R_2}{R_1 + R_2}$

D. $R_{\text{total}} = \sqrt{R_1^2 + R_2^2}$

E. $R_{\text{total}} = \dfrac{1}{2}\left(R_1 + R_2\right)$

F. $R_{\text{total}} = \dfrac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2}}$

G. $R_{\text{total}} = R_1 + R_2 - R_1 \times R_2$

H. $R_{\text{total}} = e^{R_1 + R_2}$

You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the next page.

¿ 7-1
hypothesizing/planning:

¿ 7-2
observations/data:

¿ 7-3
calculations/conclusion

I, the physics 241 laboratory TA, have examined this student's worksheet pages and found them to be thoroughly completed.

! **TA signature: ____**

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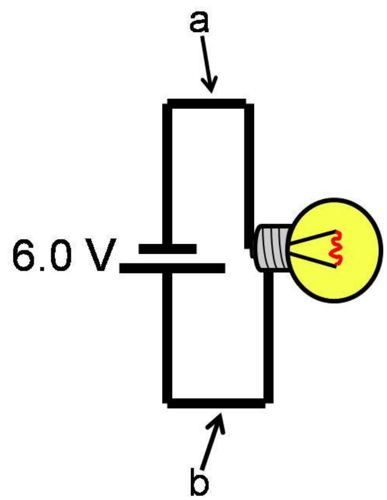
Week 1 Take-Home Quiz

Score:__________ /5

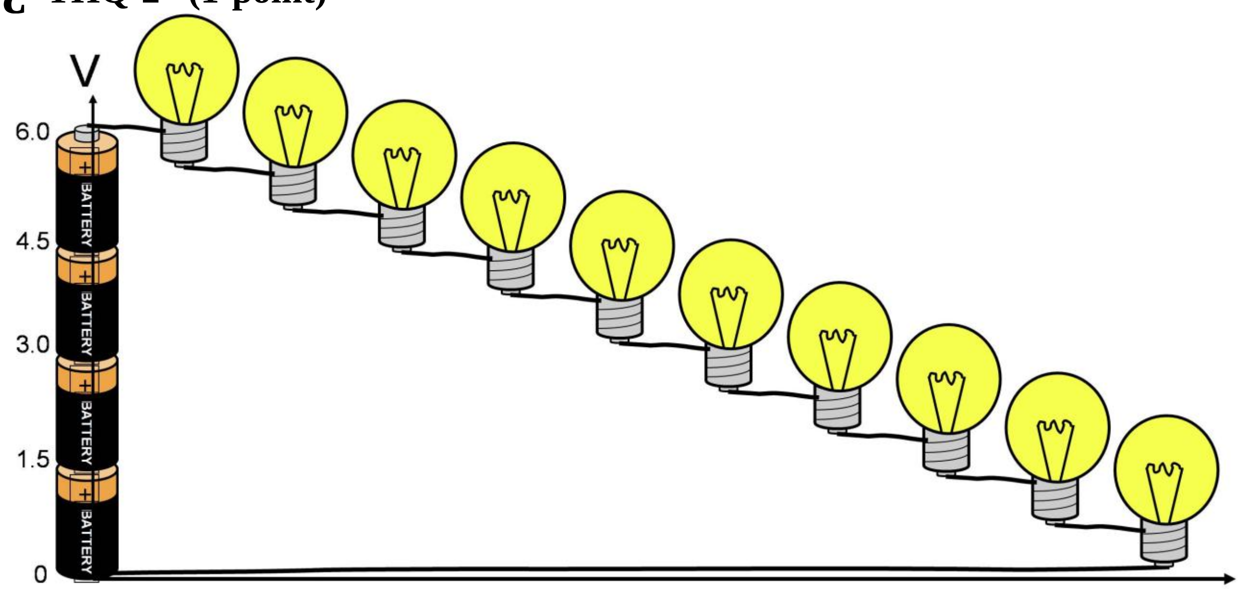
¿ THQ-1 (2-points)



a. What are the voltages at points a and b?

b. If the positive DMM lead is placed at point a and the negative DMM lead placed at point b, what reading will the DMM yield?

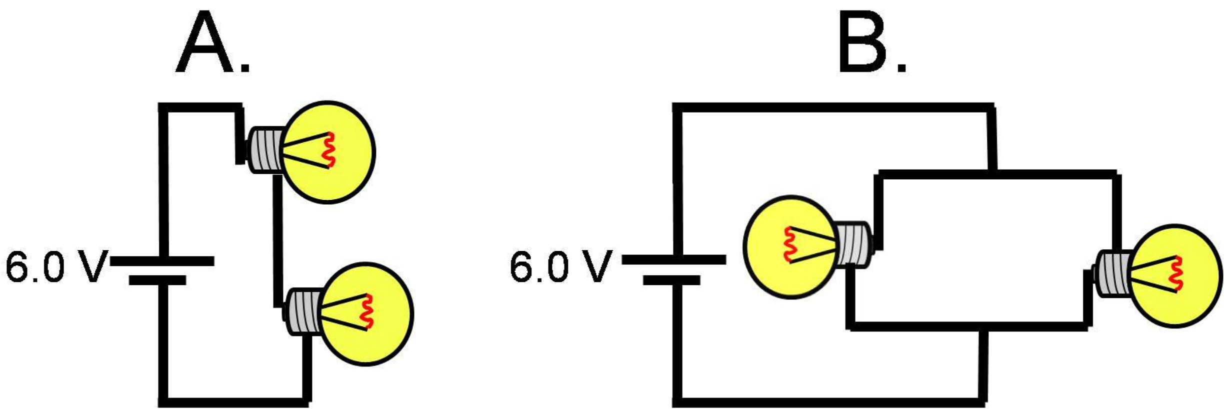
¿ THQ-2 (1-point)



There are four identical 1.5 [V] batteries in series with ten identical light bulbs. What is the voltage drop across any single light bulb?

¿ **THQ-3 (2-points)**

In the following circuits, all four light bulbs are identical.



a. Which circuit has the larger voltage drop across each bulb?

b. Which circuit has the lower equivalent resistance?

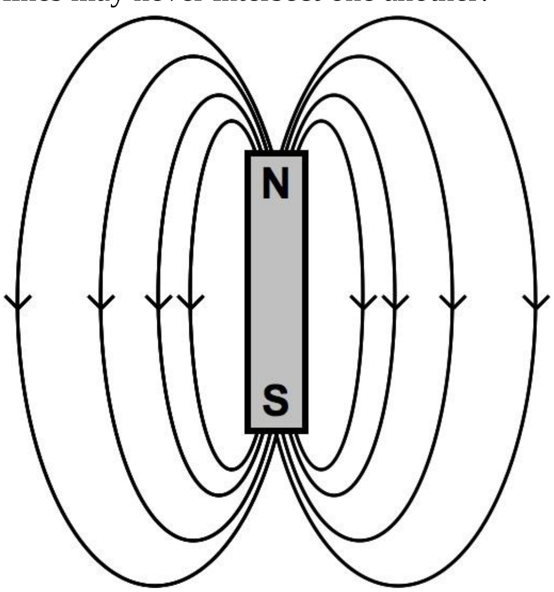
c. Which circuit draws the greater current from the voltage sources?

d. Which circuit has brighter bulbs based on your answers to a and c?

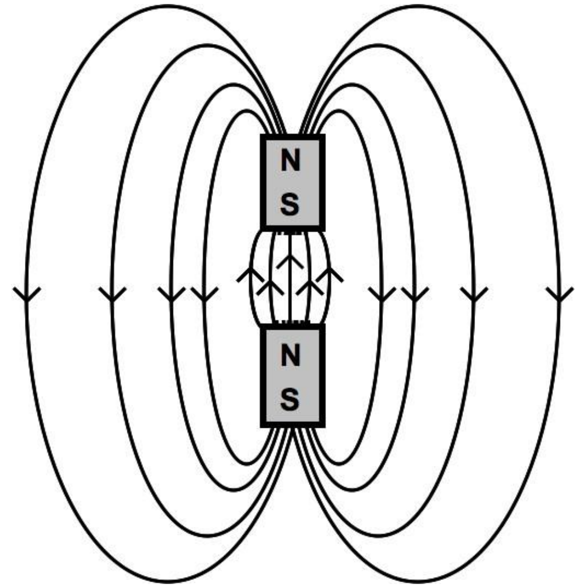
Week 2 Pre-Lab: Magnetism and Electrostatics

Read the following short pre-lab upon which you will take a quiz at the beginning of lab.

Magnetic materials create a magnetic field around them that can be represented using lines that start on the magnetic north pole(s) and end on the magnetic south pole(s). These magnetic field lines may never intersect one another!

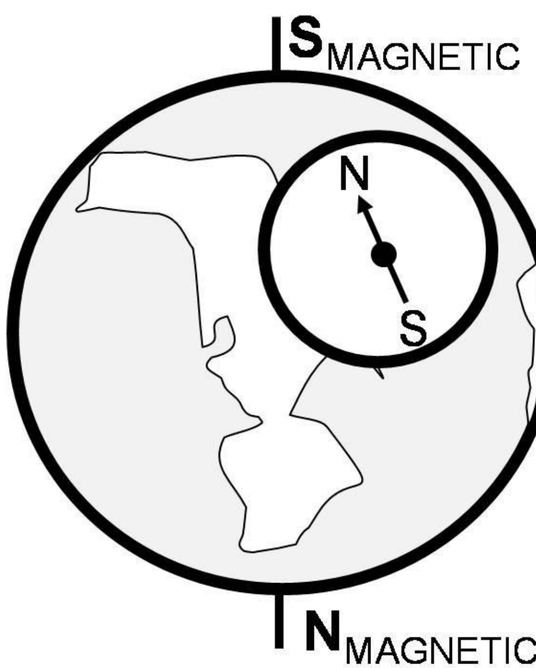


Example 1

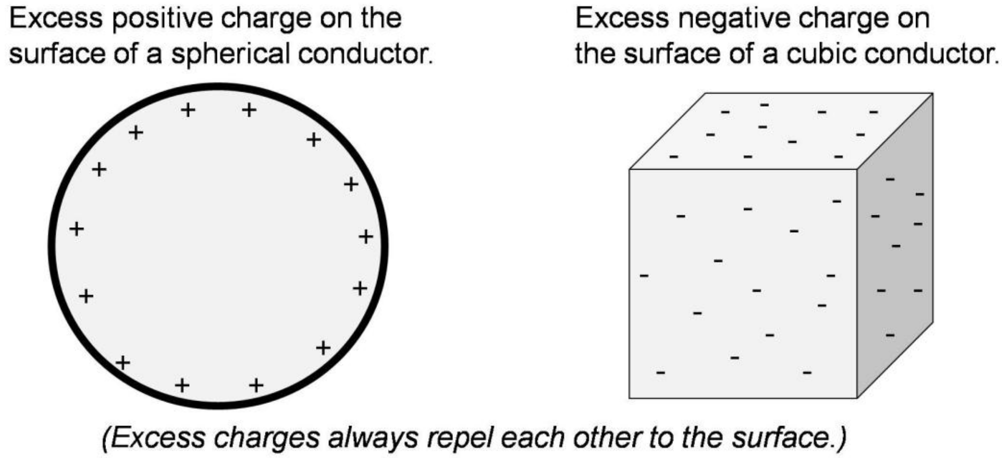


Example 2

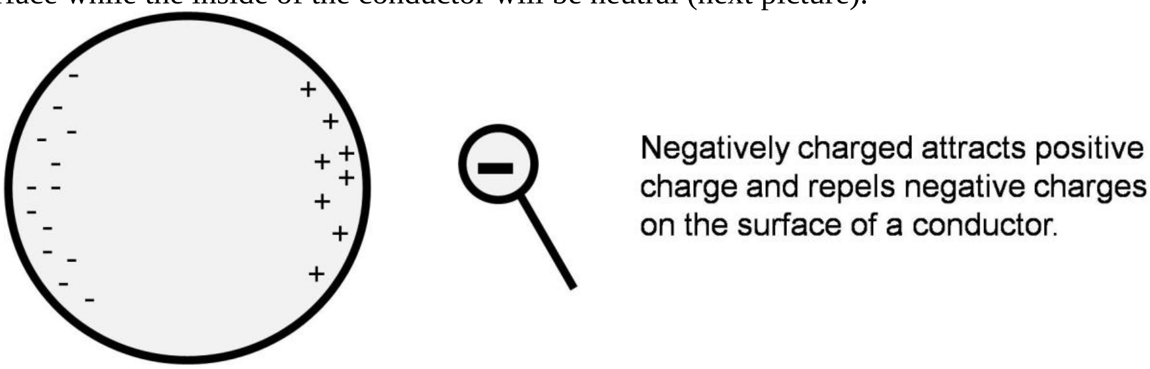
The earth's north geographic pole is really a south magnetic pole which attracts the north magnetic pole of a compass. The arrow tip of a compass is a north magnetic pole which is always attracted to the south magnetic pole of another magnet.



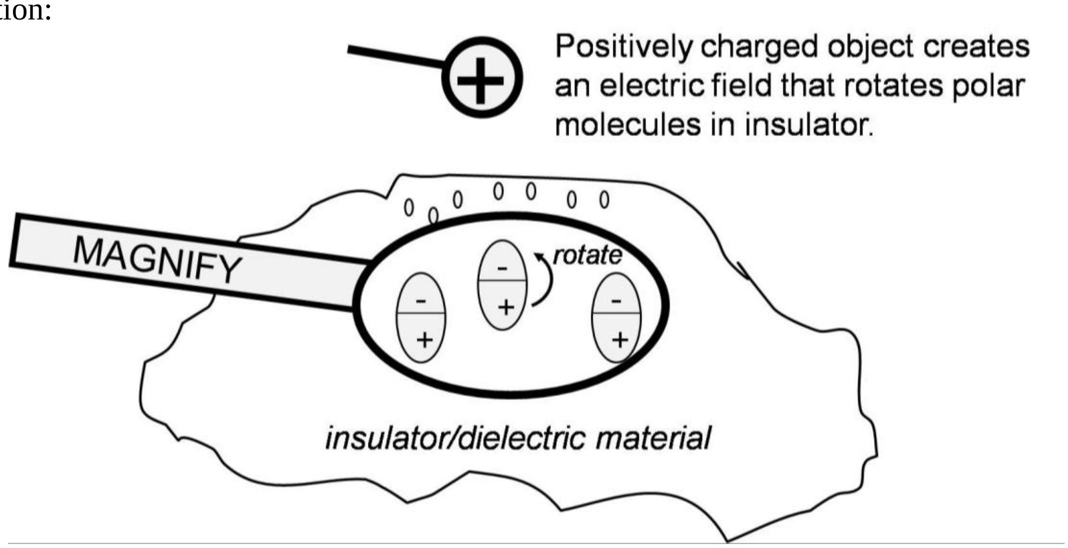
If net charge is placed on a conductor, it spreads out uniformly along the conductor surface



If a neutral conductor comes into the presence of an electric field (say from another charged object), the charges of the conductor will redistribute so that there is *macroscopic* charge separation across the entire conductor. The charges that redistribute will lie on the conductor surface while the inside of the conductor will be neutral (next picture).



Some *dielectric* insulators are made of polar molecules that can rotate at their position in the material when placed in the presence of an electric field. This leads to *microscopic* charge separation:



Week 2 Lab: Magnetism and Electrostatics

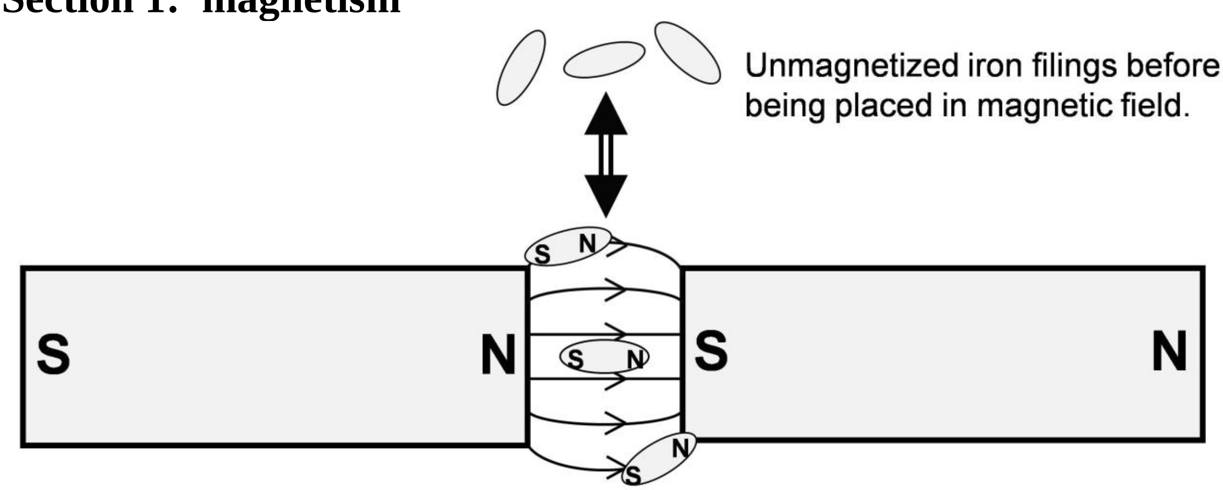
Students Absolutely Must Learn…

- How different materials with excess charge behave: conductors vs. insulators.
- How different materials with net neutral charge behave: conductors vs. insulators containing polar molecules.
- How to draw magnetic field lines (so that they don't intersect).
- How to measure the direction of a magnetic field using a compass.
- How like charges repel and unlike charges attract.
- How the process of charging by induction works.
- How to design and conduct an experiment to address an open-ended question.

! Check that your compass is aligned correctly with the Earth's magnetic field. If it is not, remagnetize it with a block of powerful magnets or get your TA to help.

! Use your compass to check the labeling of any magnets provided to you. Students in previous labs often remagnetize soft iron magnets. If your magnet(s) is magnetized incorrectly, get your TA to help you fix it (by tapping it while in a strong magnetic field or while a strong DC current moves through it; there may be a remagnetizing device in the lab).

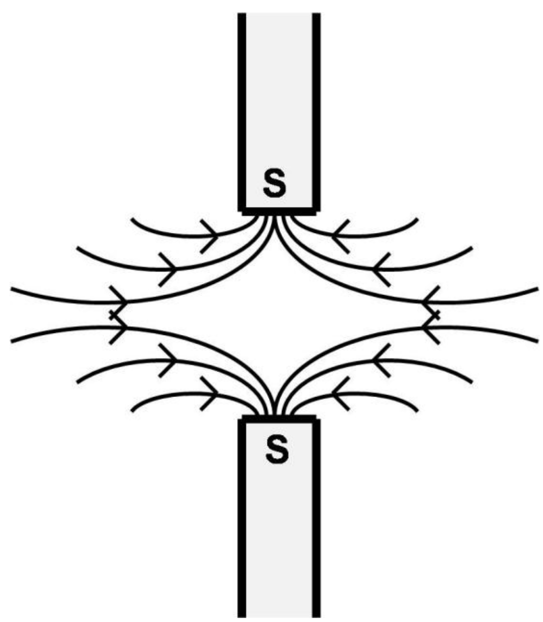
Section 1: magnetism



¿ **1-1**

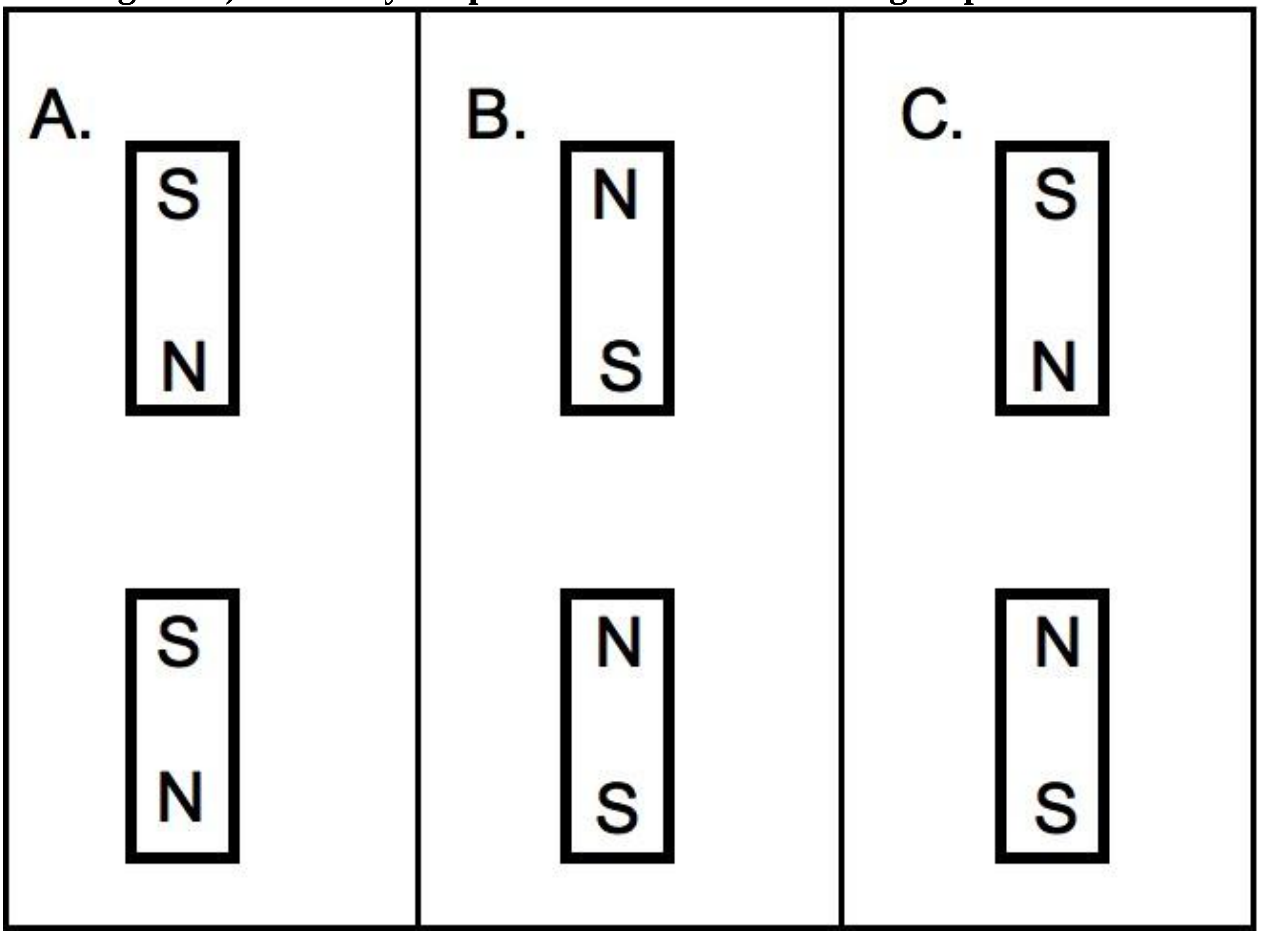
Sketch the magnetic field produced by a bar magnet by placing it underneath this worksheet and sprinkling some iron filings onto the top of your page. The flakes will show you the field lines, but you will need to sketch the direction of the field lines by identifying the magnetic poles using your compass. Don't let the magnet under the paper touch the filings or things will get messy.

The magnetic field lines for opposing magnetic poles demonstrate the repulsive force between them:



¿ **1-2**

For the following double bar magnet arrangements in the following figure, predict the magnetic field lines by sketching what you think they will look like *in the entire area surrounding the bar magnets.* (Some of the field lines will disappear out of the drawing area only to reenter in another location of the drawing area.) Discuss your predictions with other lab groups.



¿ **1-3**

Use your compass to test your prediction for each of the arrangements in the previous figure. Discuss how this checking is done and explain any inconsistencies between your measurements and predictions.

Section 2: electrostatics basics

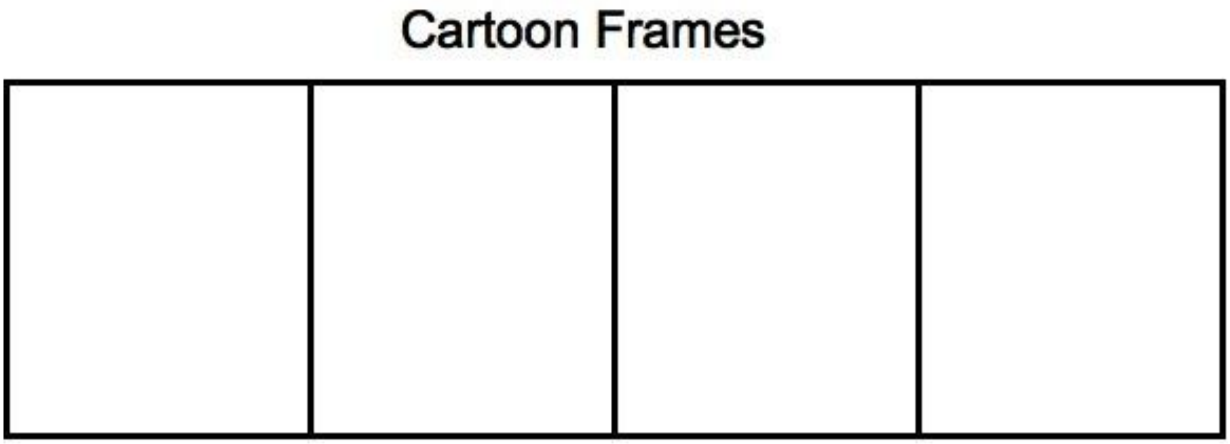
If you rub a glass or plastic rod with some fabric or synthetic fur, electrons will be transferred between the rod and the fabric leaving a charged rod with which to experiment. If the charged rod is brought into the presence of insulating material containing polar molecules, the charged rod may attract the dielectric material even though the insulating material is actually neutral by causing the rotation of the polar molecules. When the polar molecules rotate, the opposite charge will be closer to the rod so that there is a net attractive force between the dielectric insulating material and the rod. But, if the charged rod transfers some of its charge to the insulator, then both the rod and the insulator would have the same charge and thus would repel each other.

¿ 2-1

Use a charged rod to pick up little pieces of dielectric insulating material (packing peanuts or little pieces of paper). Observe the behavior of the Explain whether there is polar molecule rotation in the insulator, charge transfer between the rod and insulator, or both.

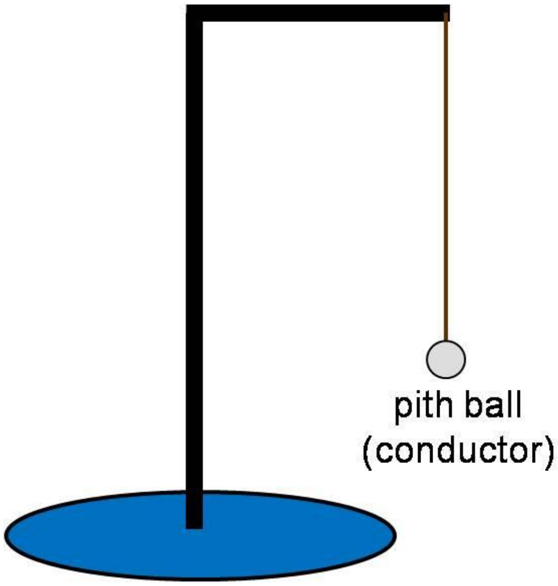
¿ 2-2

Draw a series of pictures (cartoon) with explanatory text explaining why the insulating material sticks to the rod. Use the concept of *microscopic* charge separation (dipoles). Show plus/minus signs to signify where excess charges have accumulated or dipoles to signify how charges have microscopically separated. If you do not know whether the excess charge on the rod is positive or negative, then assume it is negative.

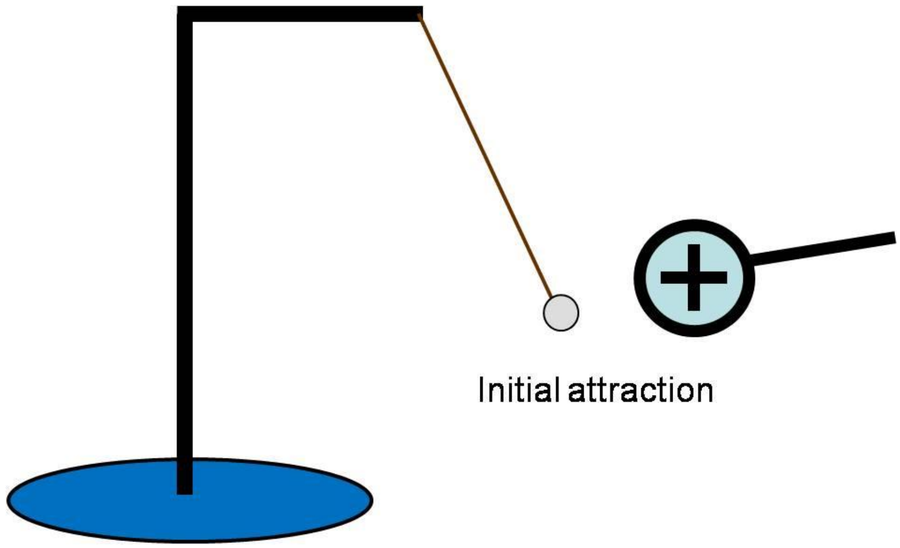


Subsection B

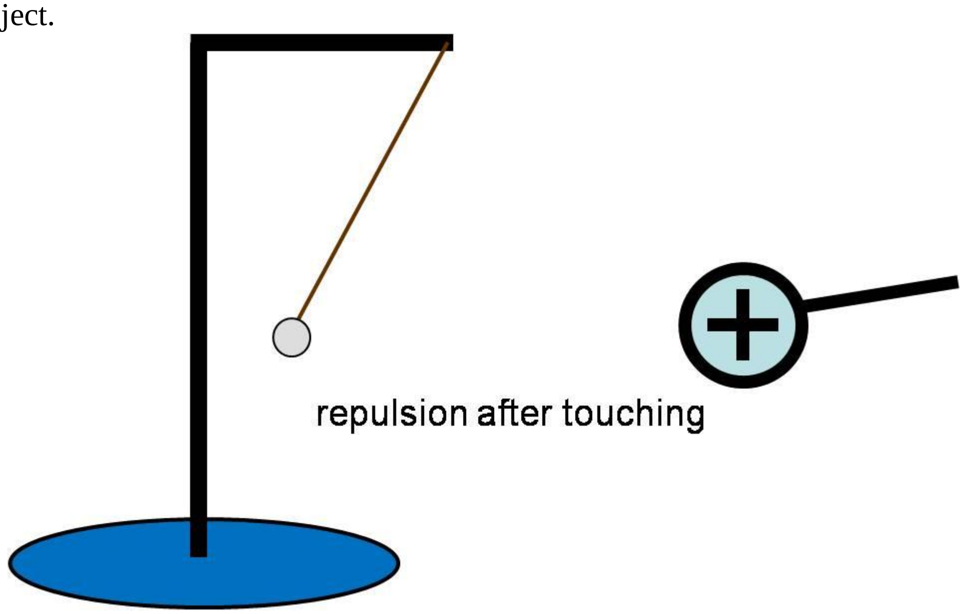
A silver coated pith ball (i.e. a conductor) has virtually no mass so we can easily see how it reacts to charge. Note that it is basically a piece of round cork covered in silver to become a conductor.



When a charged object approached the pith ball (conductor), the pith ball is at first attracted to the charged object.



However, when the pith ball touches the charged object, it immediately becomes repelled by the charged object.

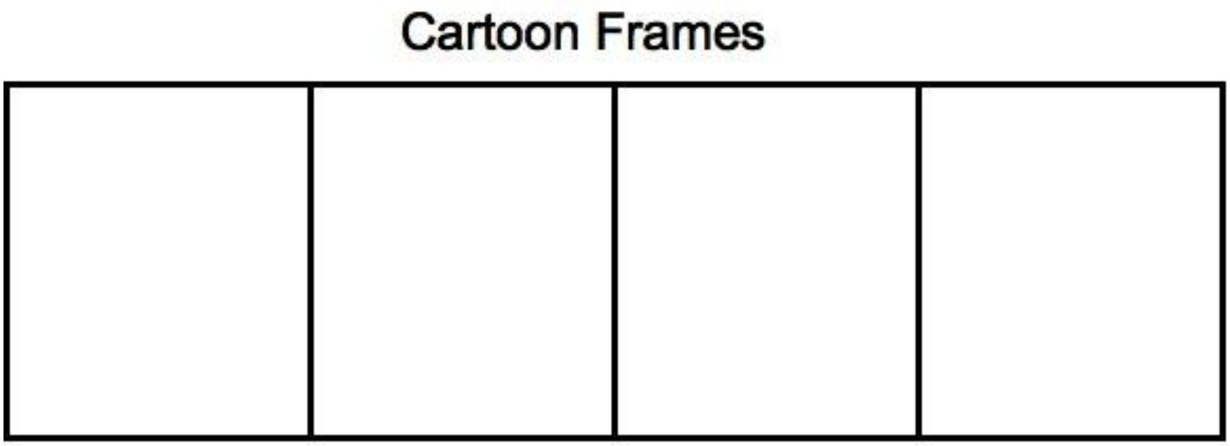


¿ 2-3

Take the charged glass rod and *slowly* bring it near the pith ball. Make observations of the behavior of the pith ball. If you do not observe the repulsive feature of the pith ball activity, then your pith ball may not have enough silver paint on it, and is therefore not a good conductor. In this case, find another lab group that has a nicely conducting silver-painted pith ball. Write your observations:

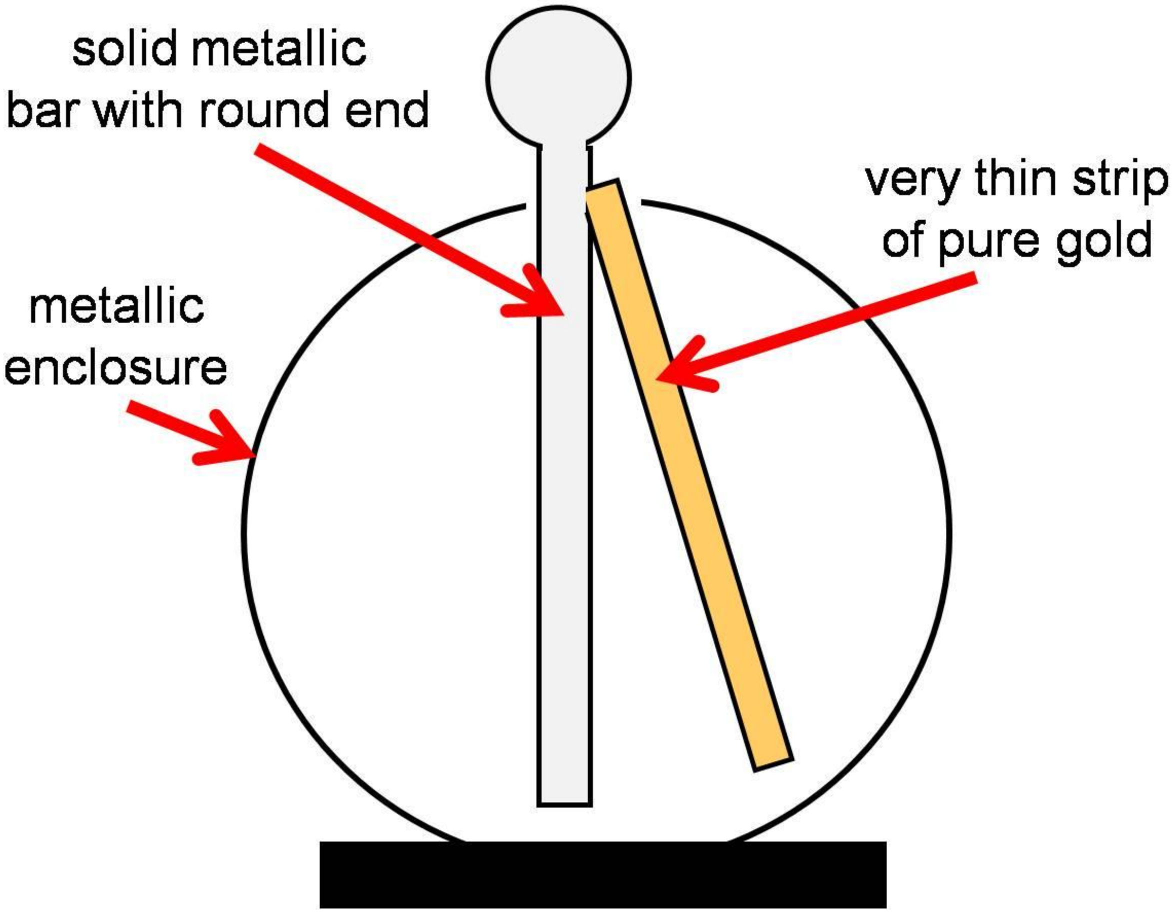
¿ 2-4

Draw a series of pictures (cartoon) with explanatory text describing why the pith ball is first attracted to the charged object, and then repelled. Use the concept of *macroscopic* charge separation on a conductor. Show plus/minus signs to signify where excess charges have accumulated signify how charges have macroscopically separated. If you do not know whether the excess charge on the rod is positive or negative, then assume it is positive.



Section 3: electroscopes

A gold leaf electroscope is a device used to detect charged objects. It is made by fastening a thin strip of pure gold to a metallic bar encased in a conducting housing. Note that the solid metallic bar and the gold strip act as a *single* conductor since they are connected. The strip of gold has been processed to be extremely thin (a few hundred atoms) so that it is actually only worth a few dollars (but a real pain to install so please don't touch it as it will disintegrate upon contact with your finger).

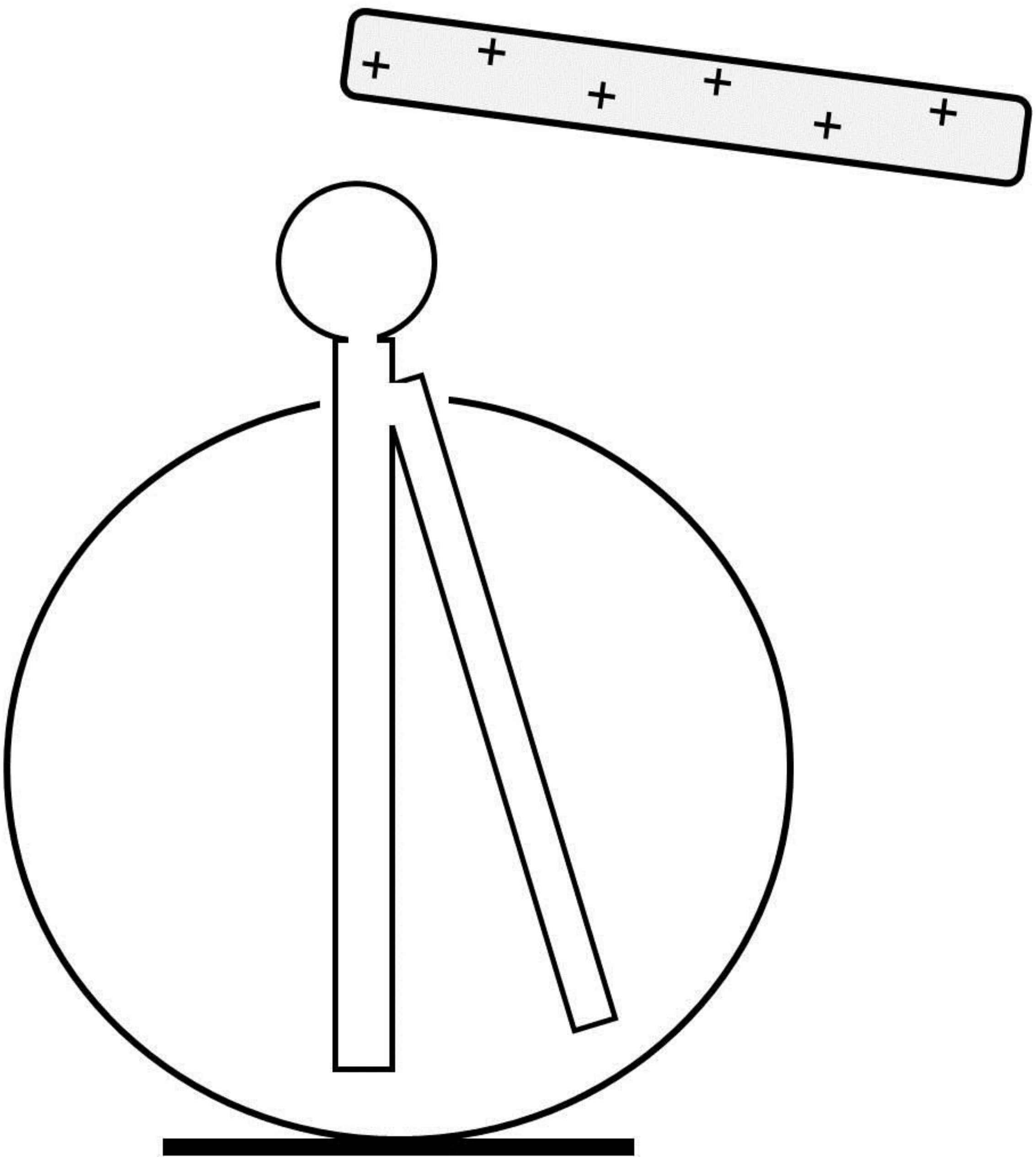


An electroscope detects excess charge by the rising of its gold leaf. The electroscope may detect the presence of a charged object that is brought near to (but *not* touching) the top of the scope through a process involving *macroscopic* charge separation. In this case, there is no excess charge on the metallic bar/gold leaf conductor. The electroscope may also be charged by touching it with a charged object. The gold leaf will still rise, but this time through a process related to the repulsion of excess charge.

! If you touch the scope with a highly charged object, the leaf will be ripped from the scope due to intense electrostatic pressure. It won't be really fun to watch, either.

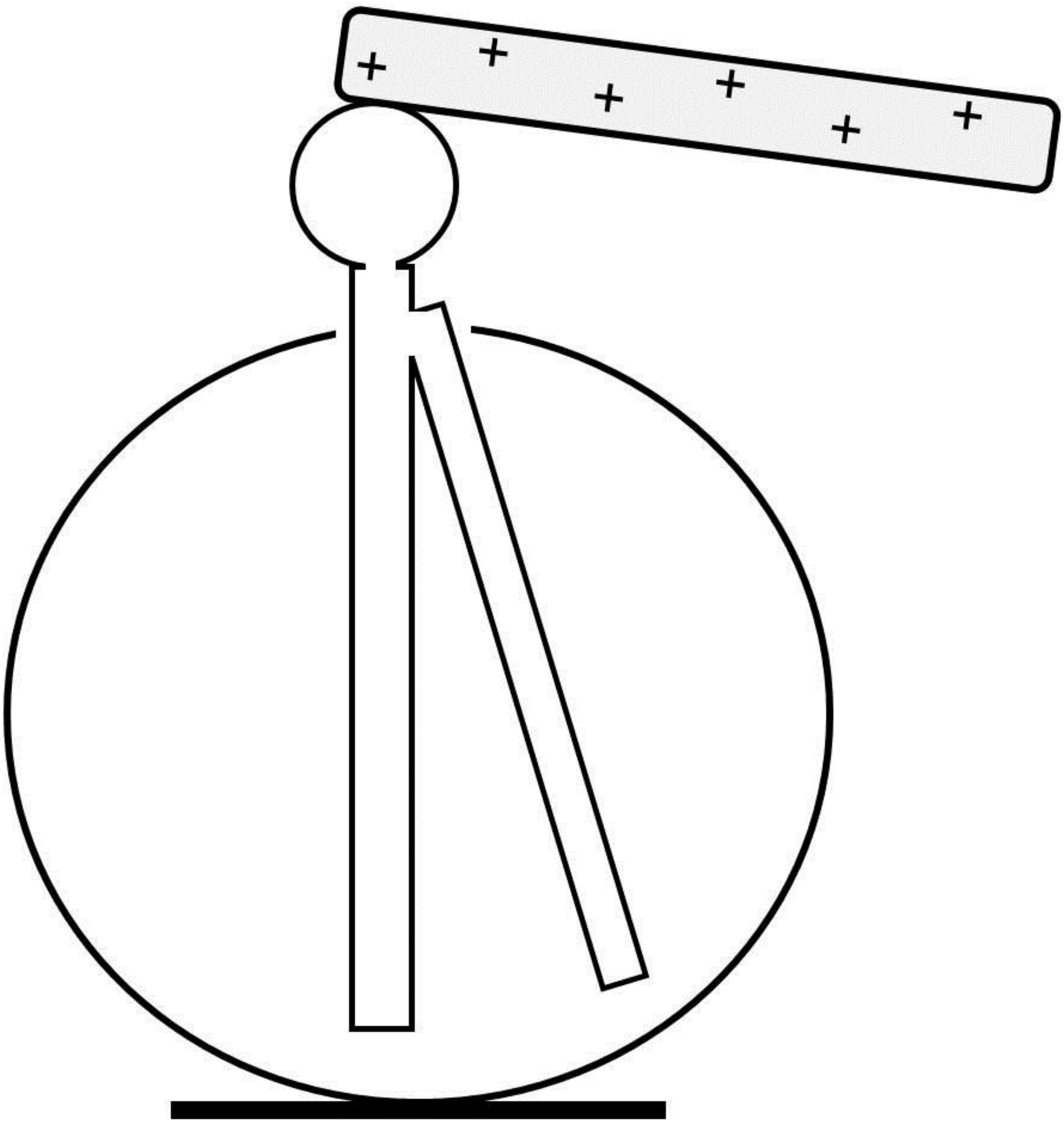
¿ 3-1 (DO NOT TOUCH THE SCOPE FOR THIS QUESTION.)

Be sure your electroscope is discharged by grounding it. Usually your body can remove any excess charge on the electroscope (so simply touch it). Now bring a positively charged glass rod near to *but not touching* the electroscope and examine the rising of the gold leaf. Use the picture-template below to show how the charges on the metallic bar/gold leaf are arranged that cause the gold leaf to rise. Do this by drawing plus and minus signs. Remember that the metallic bar/gold leaf conductor is still neutral.



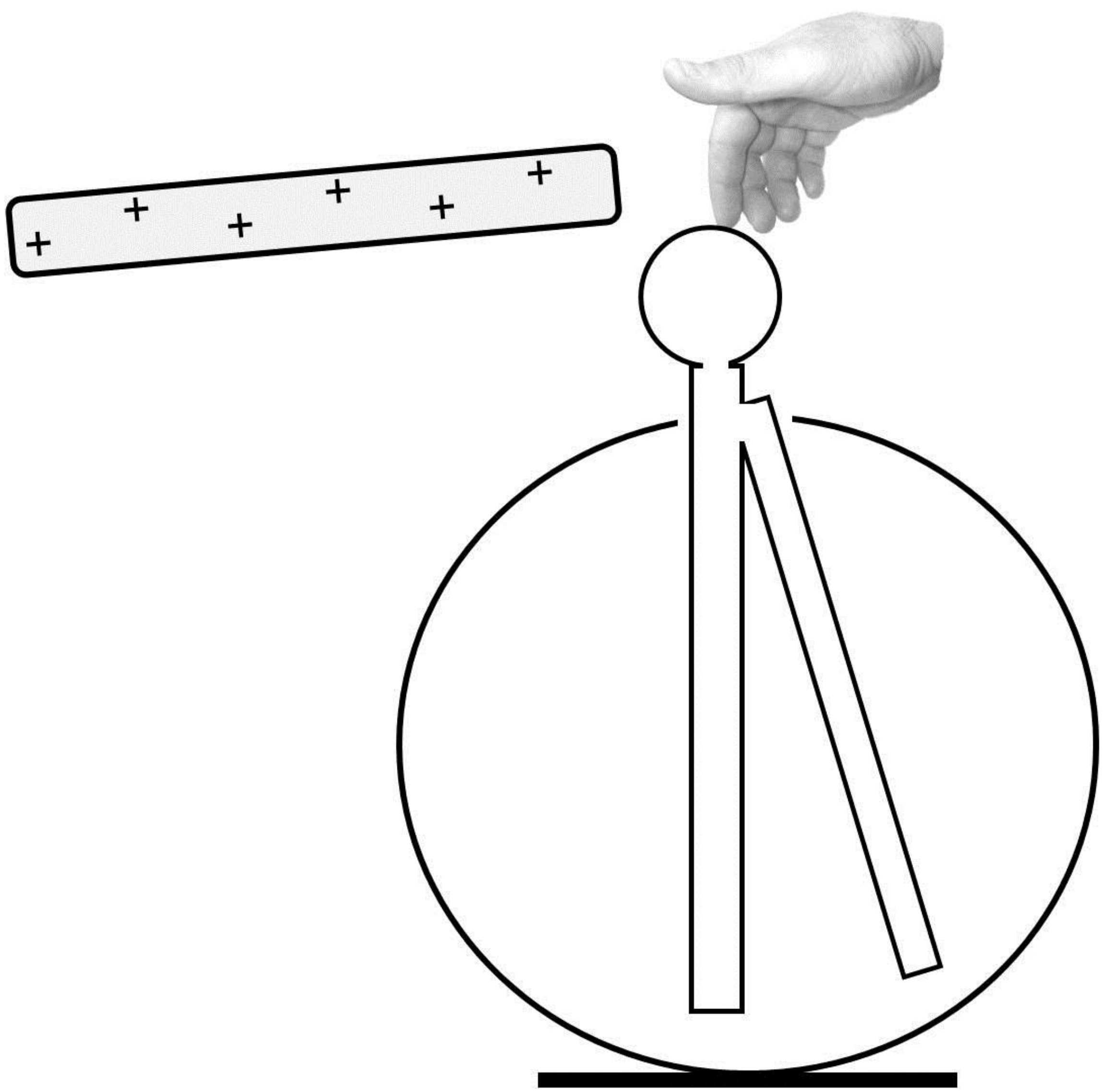
¿ **3-2 (TOUCH THE SCOPE WITH THE ROD FOR THIS QUESTION.)**

With an initially neutral electroscope, touch the end of the electroscope with a positively charged glass rod and transfer positive charge to the metallic bar/gold leaf conductor by touching the electroscope. Use the picture-template provided below to show how the charges on the metallic bar/gold leaf are arranged that cause the gold leaf to rise with plus and minus signs.



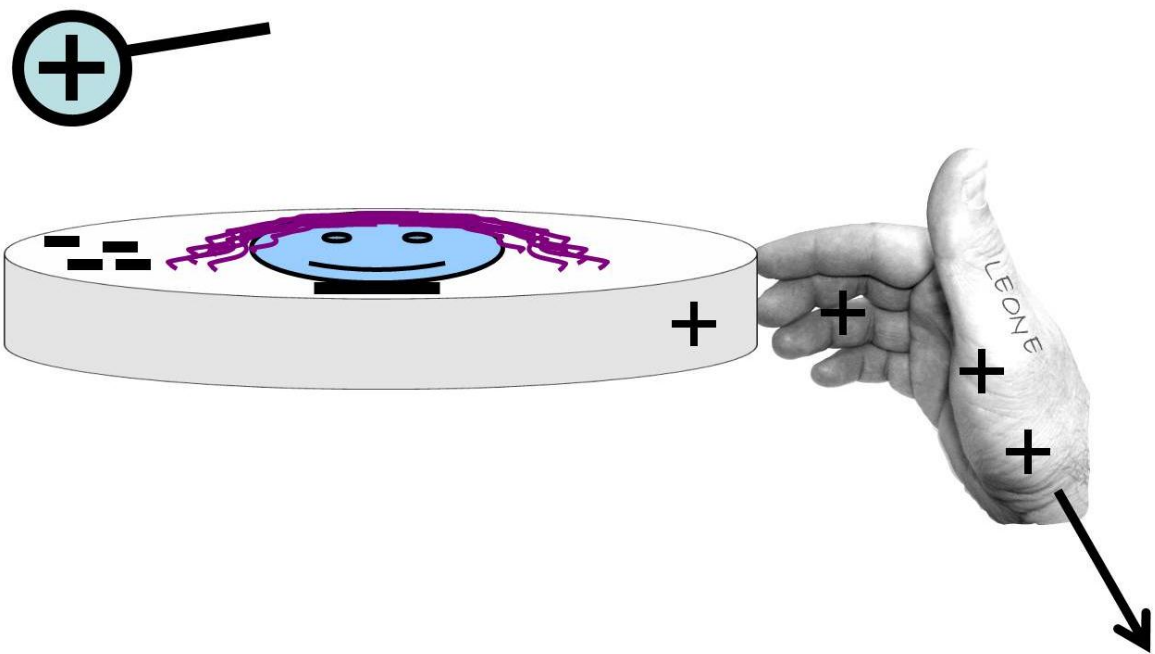
¿ 3-3 (TOUCH THE SCOPE ONLY WITH YOUR HAND.)

With an initially neutral electroscope, bring the positively charged glass rod near but don't touch the electroscope. You will have attraced negative charges to the top of the electroscope. Now touch the electroscope with your hand. Negative charges from your body will also be attracted to the rod and will be deposited on the electroscope. Remove your hand, THEN remove the glass rod and see that the electroscope has a net charge because the gold leaf is still raised. Use the picture-template provided below to show how the charges on the metallic bar/gold leaf are arranged after you touch the electroscope in the presence of the glass rod.



Section 4: charging by induction

With a little ingenuity you can charge a conductor with either positive or negative charge by using the process of induction. If you bring a neutral conductor near a positively charged object (but without touching the conductor to the charged object), and then touch the conductor with your finger, then negative charge will rush from your body onto the conductor in order to be near the positively charged object. Then remove your finger so that the negative charge remains on the conductor. If you then pull the conductor away from the positively charged object, your conductor will be negatively charged. To induce positive charge on a conductor, simply place the conductor near a negatively charged object and touch it with your finger then remove. Of course you can always charge an insulator by rubbing it with wool or imitation fur, etc.



¿ 4-1

Charge a flat sheet of plastic insulator by rubbing vigorously with fake fur. Set a flat conductor on top of it using an insulated handle (i.e. don't touch the conductor, yet). Sketch a labeled diagram of how the charge is vertically separated in the conductor while neutral overall (net charge equal to zero).

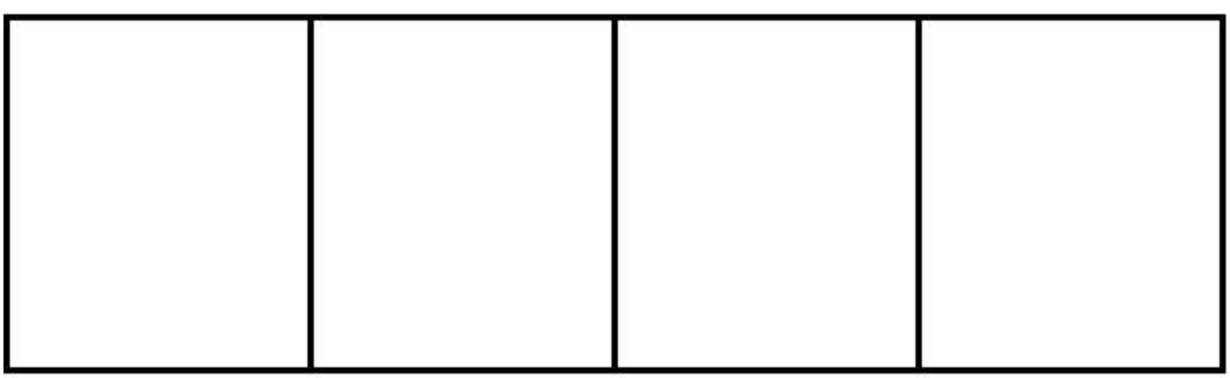
¿ 4-2

Pull the conductor from the charged insulator (still *without* touching the conductor) and see that the conductor is still neutral. Test this using the electroscope (or Faraday cage). You may detect some small amount of charge transfer to the conductor itself or the plastic handle, the conductor or even your hand because there are such enormous electrostatic fields at work. Write your observations:

¿ 4-3

Recharge your flat sheet of plastic insulator and again place the flat conductor on the plate without touching it. This time momentarily place your finger on the metal. Remove your finger and then lift the conductor disc from the plate. You may hear electrical crackling during this if your insulator was initially highly charged. DO NOT LET THIS <u>TOUCH</u> THE ELECTROSCOPE. See that your conductor now has net charge and determine the sign of the excess charge with the electroscope or Faraday cage. Make a cartoon that shows how this process of induction works and what the net charge of the conductor is (positive or negative).

Cartoon Frames



(use more frames if necessary)

Section 5: faraday ice pail

Because electrons are negatively charged, an electron always moves toward regions of *higher* electric potential (higher voltage). If you 'see' an electron move from point A to point B, then you can be sure that $V_B > V_A$.

A Faraday ice pail (made of two concentric cylindrical "cages") detects the presence of excess charge that is placed in the center of the "pail" (without touching the inner cage). If an object with positive excess charge is held inside the pail, electrons are attracted to the inner cage. This means that the outer cage must have a lower voltage than the inner wall. Since the grounding lead of the electroscope is attached to the outer cage and the positive lead is attached to the inner cage, the electroscope registers a positive voltage.

If a negatively charged object is placed inside the pail, then the electrons will be repelled to the outer cage and the electroscope will register a negative voltage.

¿ 5-1

Use the Faraday cage and electrometer to check the signs of the excess charge on several classroom objects. Make a table of your observations. Be sure to see what happens when scotch tape is placed on the table then removed. Do electrons 'stick' to the tape?

¿ 5-2

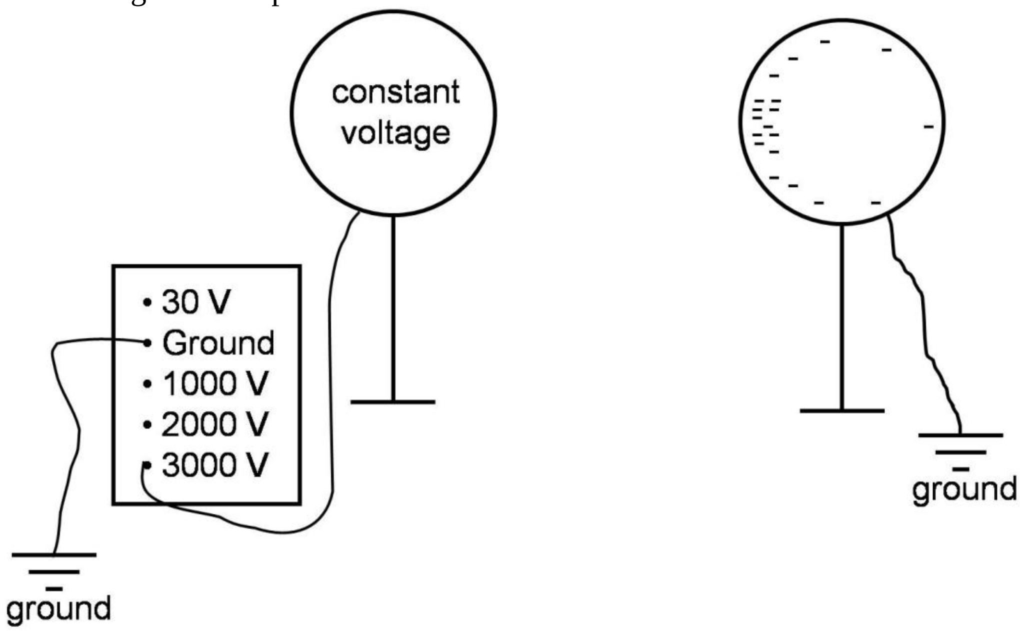
Find two *different* non-conducting insulators (blue and white paddles if equipped) and place the uncharged insulators into the pail. Rub them against each other. Since they are made of different materials, it is likely that the difference in electronegativites will cause electrons to be transferred from one material to another. Pull one insulator out of the pail at a time to determine the sign of the net charge on the paddle remaining in the pail. Even if charge is transferred between them, together they should be net neutral. If you don't observe this, then you should 1) use alcohol and hairdryers to remove any initial excess charge on the paddles (don't forget the handles) and 2) make any highly charged lab partners stand some distance away. If your lab is in a region with high humidity, it is difficult to keep significant excess charge on objects. If the air is dry, excess charge can end up *everywhere*. Record your results.

¿ 5-3

Now prove to yourself that a charged conductor will transfer charge to an uncharged conductor when they touch. Induce excess charge into a conductor (as done earlier in the lab) and record the sign of the excess charge. Take another conductor with a handle (often a paddle with a metallic face) that is initially neutral and use the Faraday ice pail to prove that it is neutral. Transfer some of the excess charge from the first conductor to the second conductor by touching them together. Prove that charge was successfully transferred from the one conductor to the other. Record your results.

Section 6: electrified sphere and grounded sphere

Two conducting spheres are provided. Connect one sphere to a voltage generator to be electrified with a large positive voltage. This sphere creates a large electric field around it that will affect any nearby spheres (including those of your neighbors!). With a second grounded sphere nearby (initially uncharged) you will use the metallic paddle and Faraday ice pail to investigate the net charge on the grounded sphere caused by the electric field of the electrified sphere. An illustrative picture is provided that may or may not correctly show the charge distribution on the grounded sphere.



¿ 6-1
Experimentally determine if the grounded sphere has a net charge, or if it is simply neutral with macroscopic charge separation?

¿ 6-2
If the grounded sphere has a net charge, explain where this excess charge came from.

¿ 6-3
Experimentally determine if the grounded sphere has a similar charge distribution to that shown in the figure, or if the figure is wrong.

Section 7: authentic assessment

Magnets surround you in your everyday life. How upsetting it is to think that most people are incapable of determining a simple north or south pole on an unlabeled magnet.

If you are uncomfortable having another student check your work, please ask your TA.

¿ 7-1

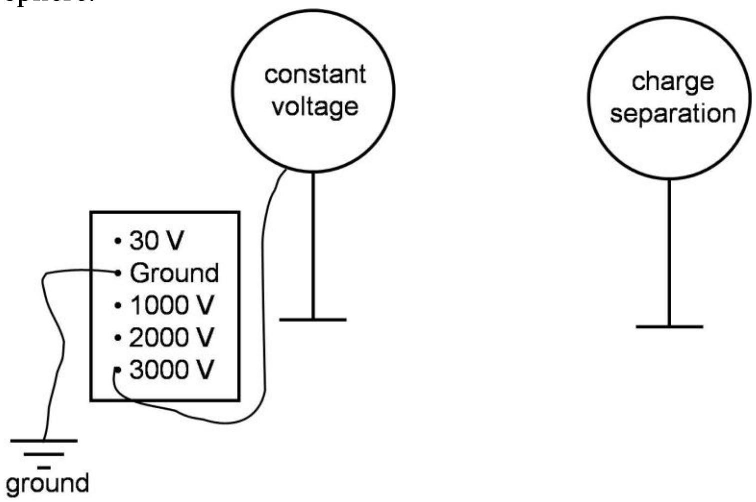
Find an unlabeled magnet in the lab and use a compass to determine the north pole of the unlabeled magnet. First be sure your compass agrees with the Earth's magnetic field. *Explain* your work to a student in a different lab group as you show them your solution.

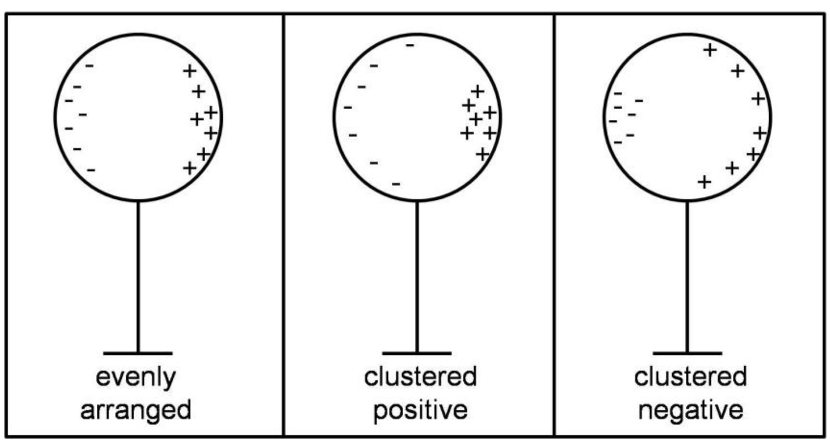
"Yes, I have seen this student determine the north pole of an unlabeled magnet and their verbal explanation of the process is correct. They are well-prepared for owning a refrigerator!"

Student
Signature:____

Section 8: open-ended

If one conducting sphere is charged to a constant positive electric potential (voltage), and another neutral (ungrounded) conducting sphere is brought near to it, then the charge on the neutral sphere will separate. On the second sphere, a certain amount of negative charge will be attracted to the sphere held at the constant positive potential, and an equal amount will be repelled. It is extremely difficult to calculate the arrangement of charge on the neutral sphere. Sometimes a mathematical theory is of little use in a complex system and you just have to experiment to get answers. Figure out a way to determine the arrangement of the separated charged on the ungrounded neutral sphere.





You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the next page.

¿ 8-1
hypothesizing/planning:

¿ 8-2
observations/data:

¿ 8-3
calculations/conclusion

I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: ____**

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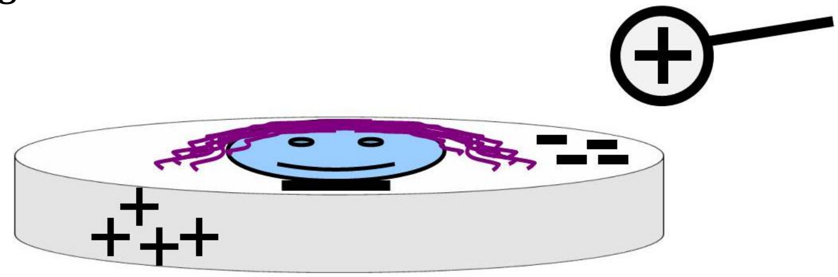
Week 2 Take-Home Quiz

Score:__________ /5

¿ THQ-1 (1-point)

The following picture shows a neutral conducting disc in the presence of a positively charged conductor. Choose which would happen to total charge of the conducting disc if it was momentarily touched by the positively charged object:

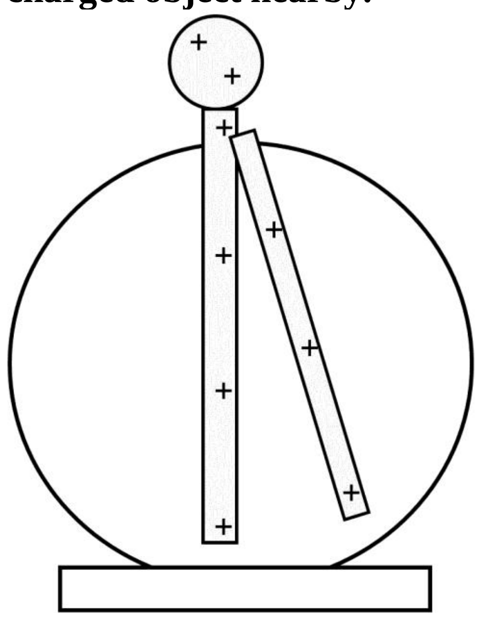
a) become negatively charged
b) stay neutral
c) become positively charged



¿ THQ-2 (1-point)

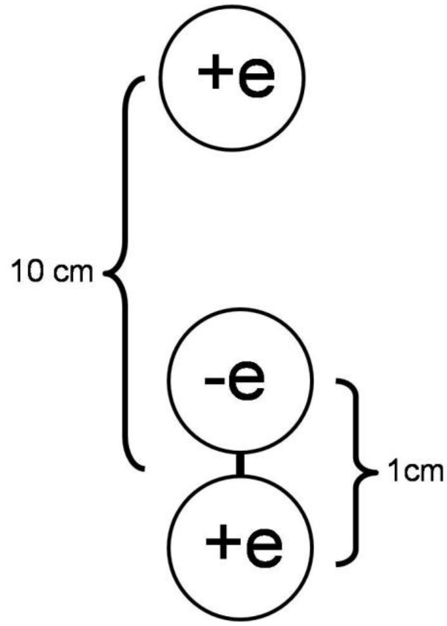
Choose the best explanation for why the gold leaf is raised in the below picture:

a) It has been touched by a negatively charged conductor.
b) It has been touched by a positively charged conductor.
c) There is a negatively charged object nearby.
d) There is a positively charged object nearby.



¿ **THQ-3 (3-points)**

Use the following figure of a dipole in the presence of a single charge to understand why a charge attracts a polarizable molecule.



Calculate the attractive net force in [newtons] between the upper charge and the dipole beneath (two rigidly connected opposite charges). It is 10 [cm] to the *midpoint* of the dipole (so add or subtract 0.5 [cm] for distances).
Note that $e = 1.6 \times 10^{-19}$ [C] and $k_E = 9 \times 10^{9}$ [N m^2 / C^2].

Unit 2 Lab Report Instructions

Unit Lab Report [40 points]

Use the following section titles in your report. Images, text or equations plagiarized from the internet are not allowed! Remember to write your report *alone* as collaborating with a lab partner will make you both guilty of plagiarism. **Please label your lab report sections:**

- **Title [0 points]** – A catchy title worth zero points so make it unique and fun.
- **Mini-Report [10 points]:** ***{4-6 paragraphs, ~2 double-spaced pages}***
  Choose **one** of the following sections about which to write your mini-report:
  Week 3 Section 2 or Week 4 Section 2
  Write a "mini-report" for one particular section of the lab manual. Describe what you did succinctly, and then what you found accurately. Then explain what the result means and how it relates to some of the concepts in the previous section. *You must write using sentences & paragraphs; bulleted lists are unacceptable.* ***Please label your mini-report sections:***
  - **Abstract:** Write 2-3 sentences about the goals of this section. Describe the concepts you were investigating and how the experimentation you performed allowed you to investigate these concepts. Write 2-3 sentences summarizing the procedure. Write 2-3 sentences summarizing the results and what the results mean with regard to the concepts you were investigating. *It is best to write the abstract last*.
  - **Procedure:** Do not provide a lot of specific details, but rather you should summarize the procedure so that a student who took the course a few years ago would understand what you did.
  - **Results:** Provide a description of the data you obtained such as data tables. Restate any measured values, calculated slopes of lines-of-best-fit, etc. Do not *interpret* your results, save any interpretation for the discussion.
  - **Discussion:** Analyze and interpret the results you observed/measured in terms of some of the concepts and equations of this unit. It is all right to sound repetitive with other parts of the report.
- **Open-Ended Discussion [10 points]** – ***{1-2 paragraphs, ~1 page double-spaced}*** Choose **one** of the open-ended experiments from the two weekly activities to write about. Describe your experimental goal and the question you were trying to answer. Explain the ideas you came up with and what you tried. If your attempts were successful, explain your results. If your attempts resulted in failure, explain what went wrong and what you would do differently in the future. *You must write using sentences & paragraphs; bulleted lists are unacceptable.*
- **Graphs [5 points] - {attach to your typed report}** Graphs must be neatly hand-drawn <u>during lab</u> on graph paper. Your graphs must fill the entire page (requires planning ahead), include a descriptive title, labeled axes, numeric tic marks on the axes, and unit labels on the axes. If instructed to calculate the slope of the line-of-best-fit, write it directly on the graph.
  Week 3: 2-1 to 2-5 (one graph), 3-1, 4-1 to 4-2 (one graph)
  Week 4: 2-3, 2-7, 2-11
- **Take-Home Quizzes [2x5 points = 10 points] - {attach after your Graphs}**
- **Selected Worksheet Pages [5 points] - {attach after your Take-Home Quizzes }**
  Your TA will choose which pages you need to hand in.

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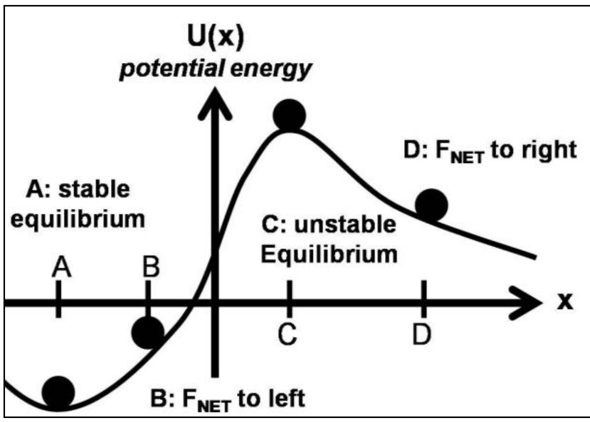
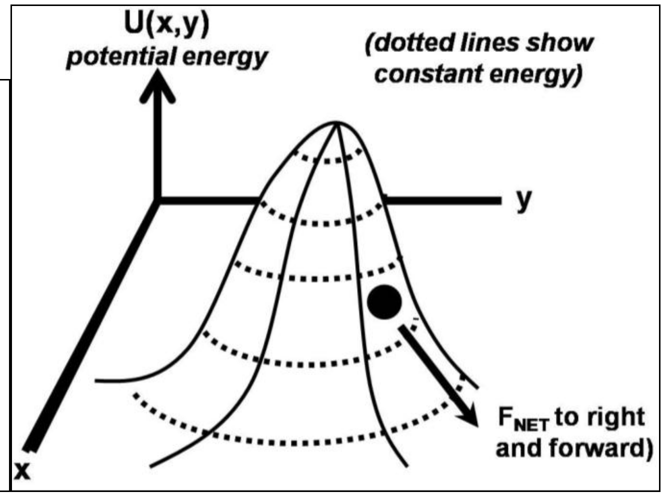
Week 3 Pre-Lab: Electric Field Mapping

Read the following short pre-lab upon which you will take a quiz at the beginning of lab.

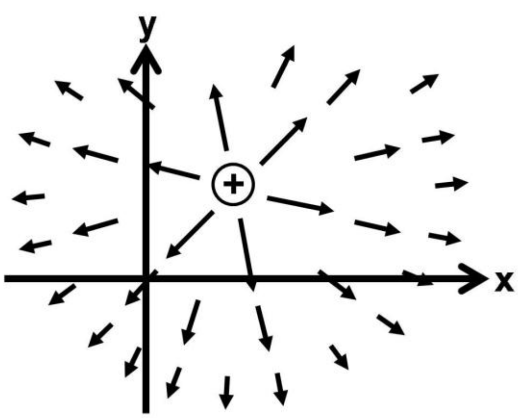
A graph of the potential energy for an object shows the forces it experiences since the object will seek to "roll downhill" to the position of lowest potential energy. The steeper the slope, the stronger the force pushing the object downhill.

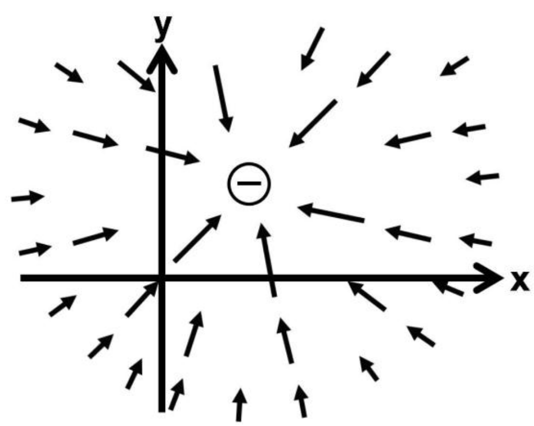




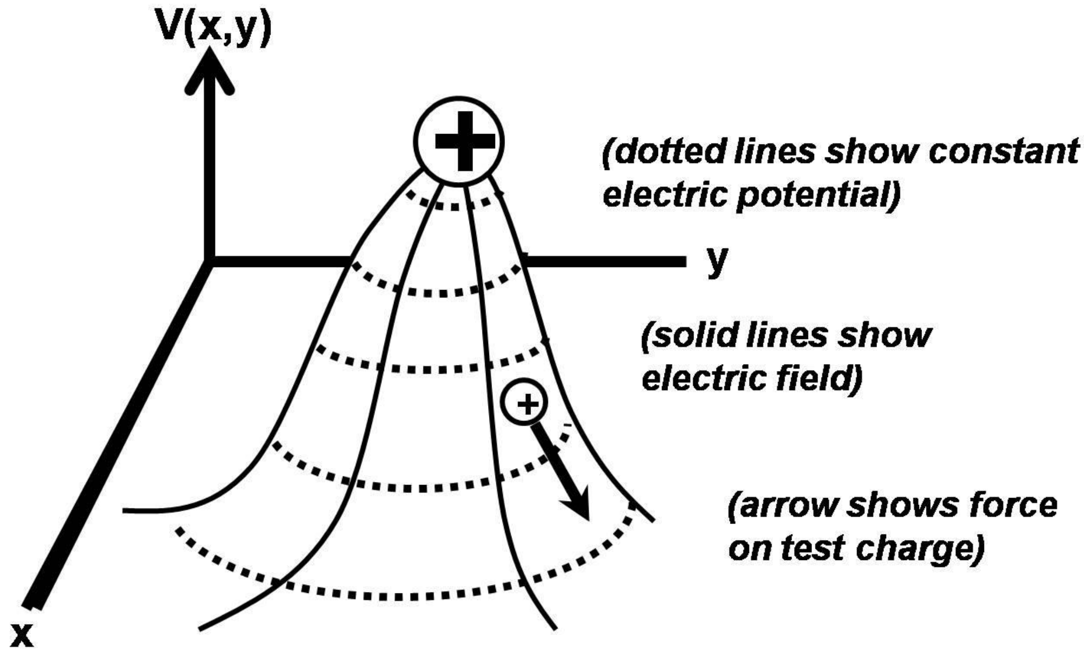
(one dimensional) **(two dimensional)**

A charge creates an electric field around it. This electric field can be described by drawing vector arrows around the charge with the size of the vectors representing the strength of the field at that point in space. Note that the strength of the electric field decreases as you move away from the charge. The electric field points away from positive charges and toward negative:

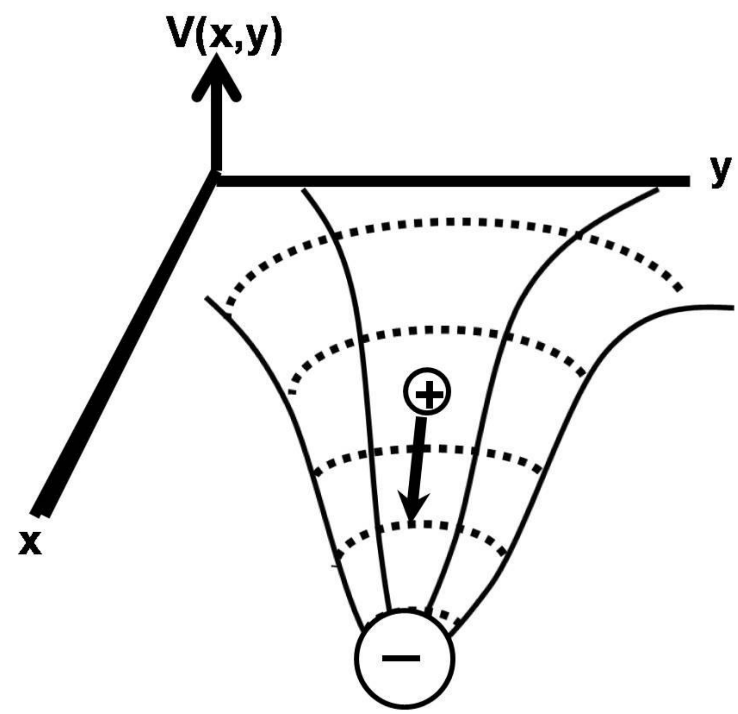




A positively charged object creates a “mountain” of voltage that positive charges will be forced to “roll downward” (and negative charges will attracted upward).



Similarly, a negatively charged object creates a “valley” of voltage that a positive charge will be forced to “roll downward” (and negative charges will be repelled upward):



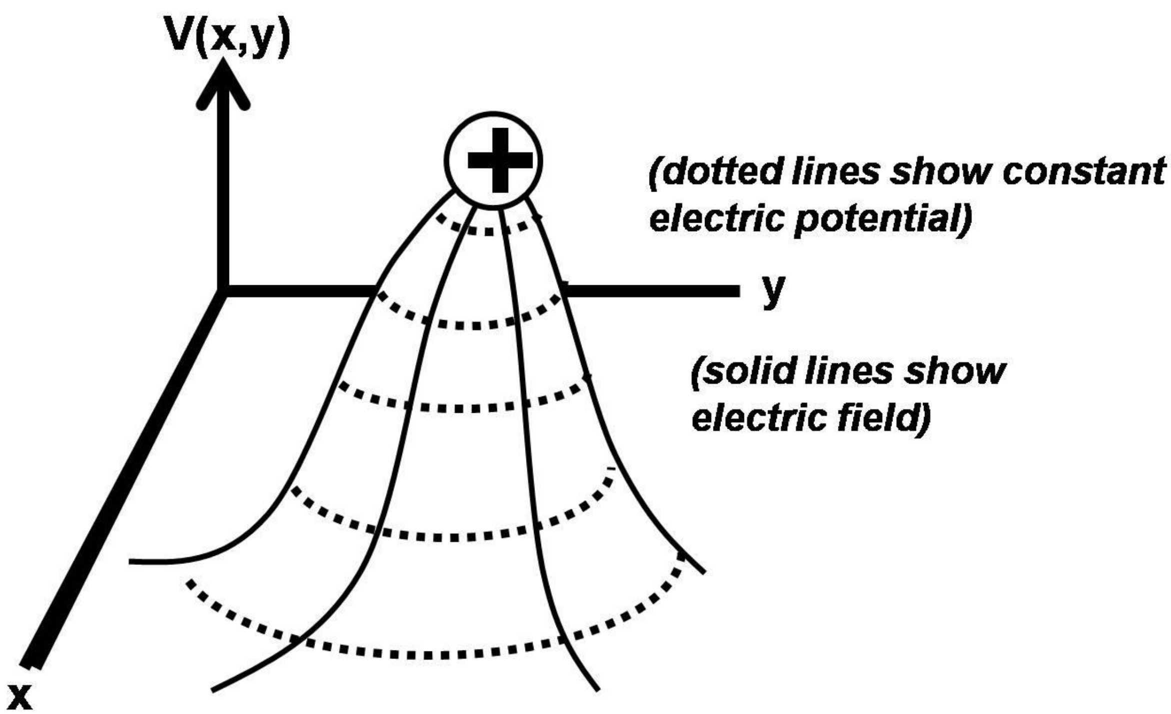
Thus, positive charges move from areas of high voltage to low voltage while negative charges move from low voltage to high voltage.

Week 3 Lab: Electric Field Mapping

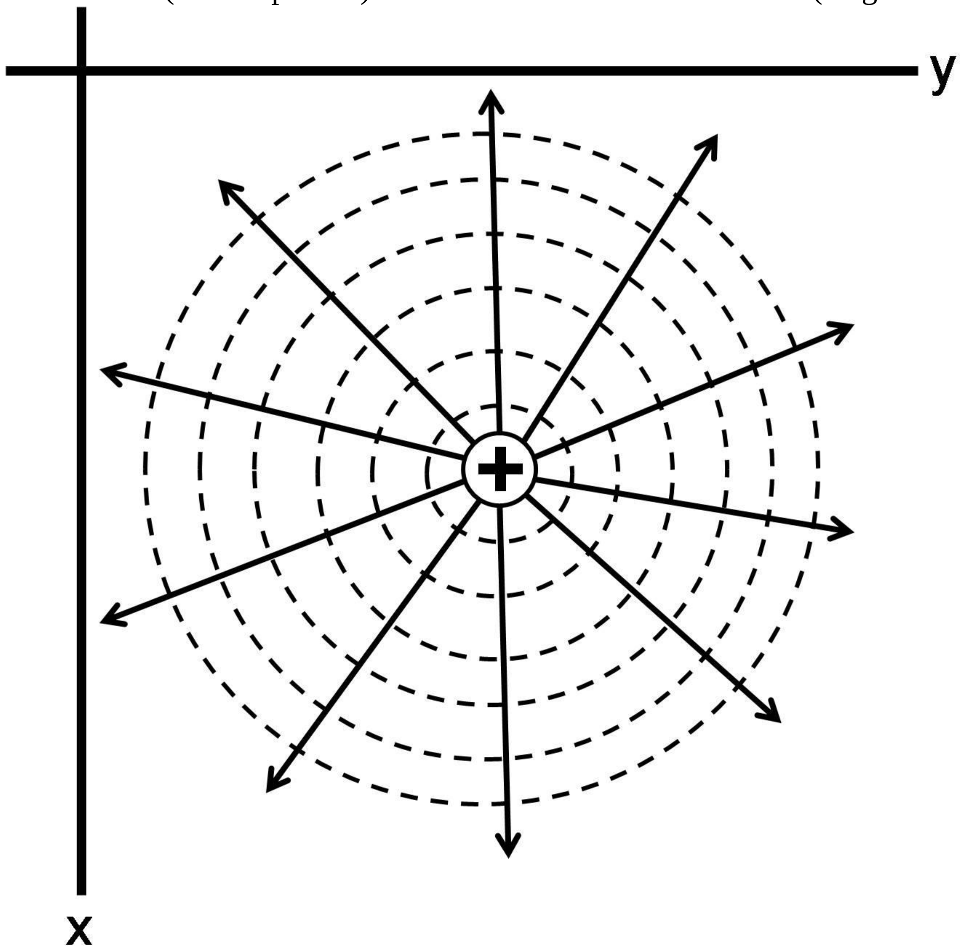
Students Absolutely Must Learn…

- The relationship between potential energy and force, visually and mathematically.
- The relationship between electric potential and electric field, visually and mathematically.
- How to calculate partial derivatives.
- The difference between vector fields and scalar fields.
- How to visualize a vector field with arrow graphs.
- How to visualize a vector field with field lines.
- How electric fields cause electric forces on charged particles.
- How to draw equipotential lines and electric field lines.
- How to estimate electric fields from electric potential measurements.
- How positive charges lower their electrical potential energy by moving to lower voltages.
- How negative charges lower their electrical potential energy by moving to higher voltages.

Section 1: sketching electric fields



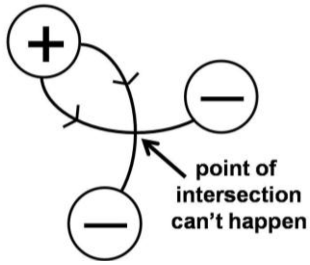
If you examine a two dimensional electric potential landscape (first picture) from above you will see an 'aerial view' (second picture) that obscures the third dimension (height or voltage):



Nevertheless, if you know that the middle is supposed to have a higher electric potential (voltage), then you can imagine that each sequentially outward dotted ring represents a lower step down the 'voltage mountain'. The solid lines show the direction of electric field, but without arrowheads so that you must figure out the direction yourself. That is not hard because electric fields always point in the direction of lower electric potential ("down the voltage hill"). Also note that electric field lines are always perpendicular to equipotential lines where they intersect.

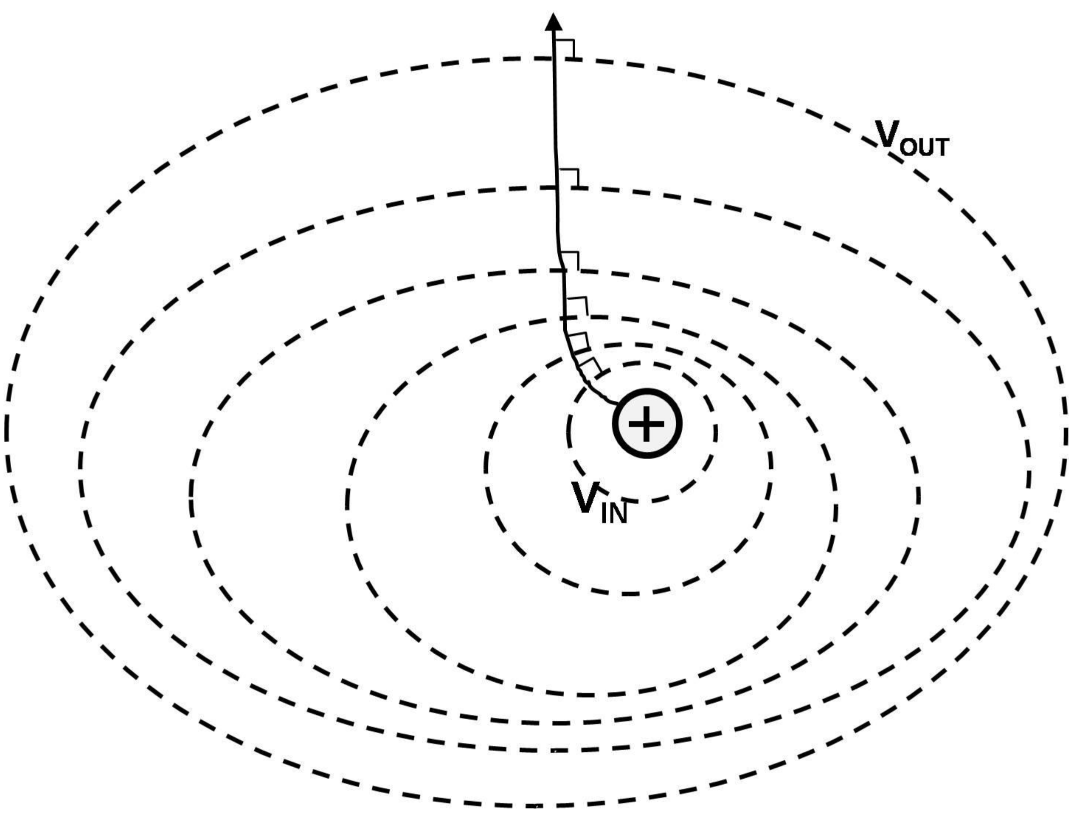
What is not obvious is where the electric field and thus forces on test charges would be the strongest. A good rule of thumb is that the strength of the electric field is largest where the density of electric field lines is greatest. This would imply that the electric field magnitude is greater nearer to the center of the system.

Also, just as with magnetic field lines, electric field lines cannot intersect. If they did, it would be ambiguous in which direction a test charge would feel a force if it were at that point. But the force direction caused by an electric field is always unique so such crossings cannot happen. If you draw electric field lines crossing, it makes it easy for your TA to mark your answer wrong!



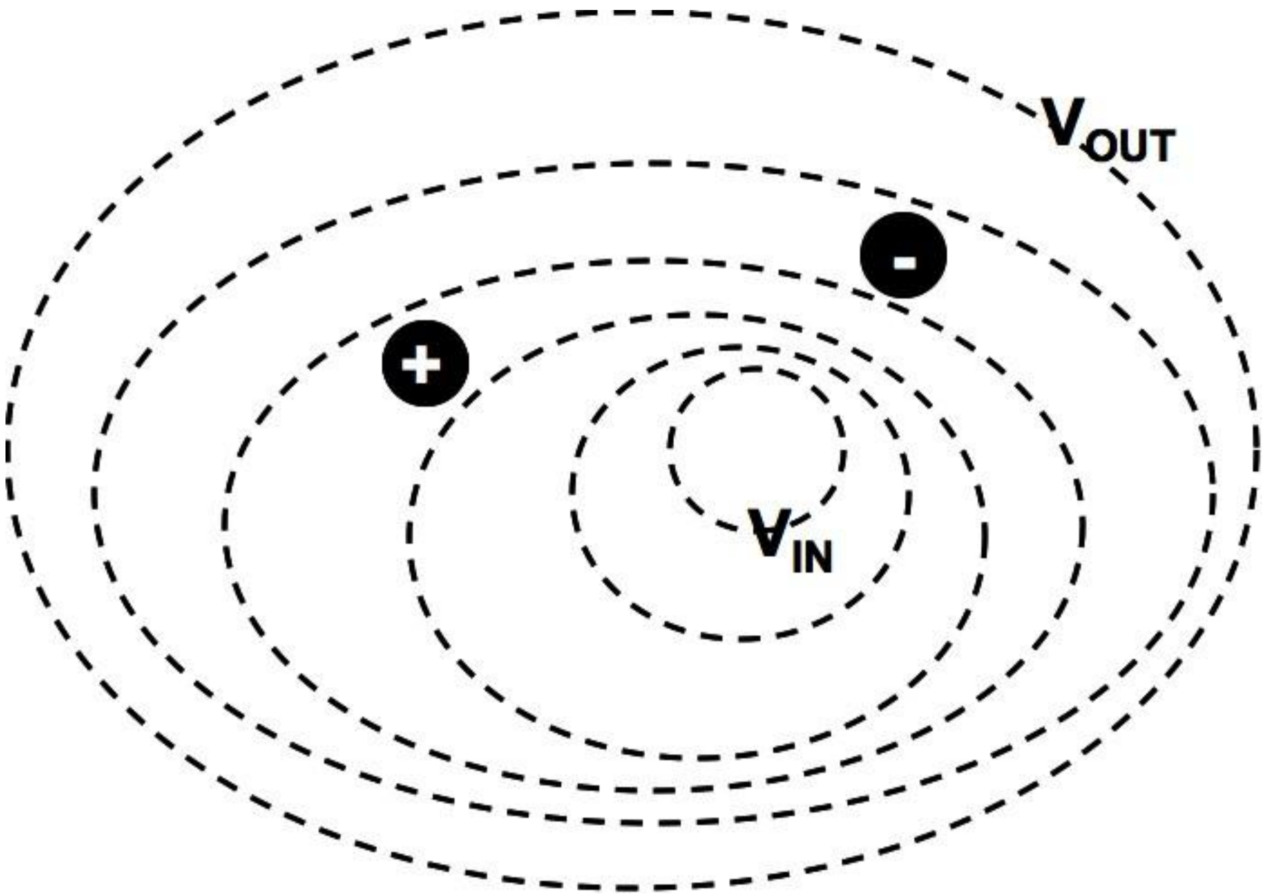
¿ 1-1

In the following picture depicting equipotential lines (dashed lines of constant voltage), sketch the corresponding electric field lines (draw the electric field lines with solid lines). Be sure to label the direction of the electric field lines using arrows using the assumption that $V_{OUT} < V_{IN}$. Note that V_{out} gives the value of the voltage for the entire dotted line it touches (similarly for V_{in}). Think topographical maps! Draw on the picture below; an example field line is shown on the picture. Note the perpendicular symbol is used to emphasize the electric field line intersecting the equipotential line perpendicularly. You do not have to draw the perpendicular symbols.



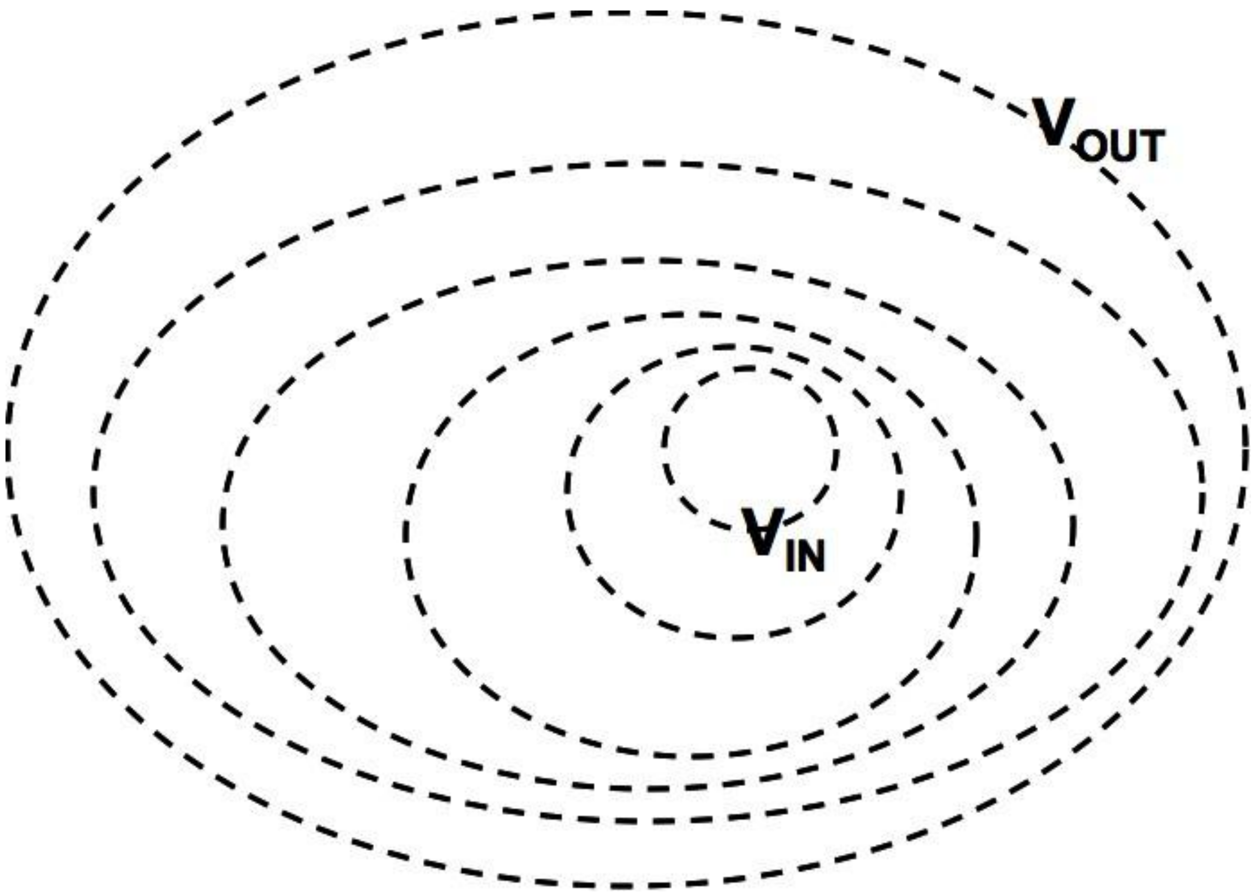
¿ 1-2

In the following picture assume $V_{OUT} < V_{IN}$. Describe how each of the two test charges shown would move if placed where shown using arrows to show the direction of each charge's acceleration vector. *Draw on the picture below and write an explanation below the picture.*



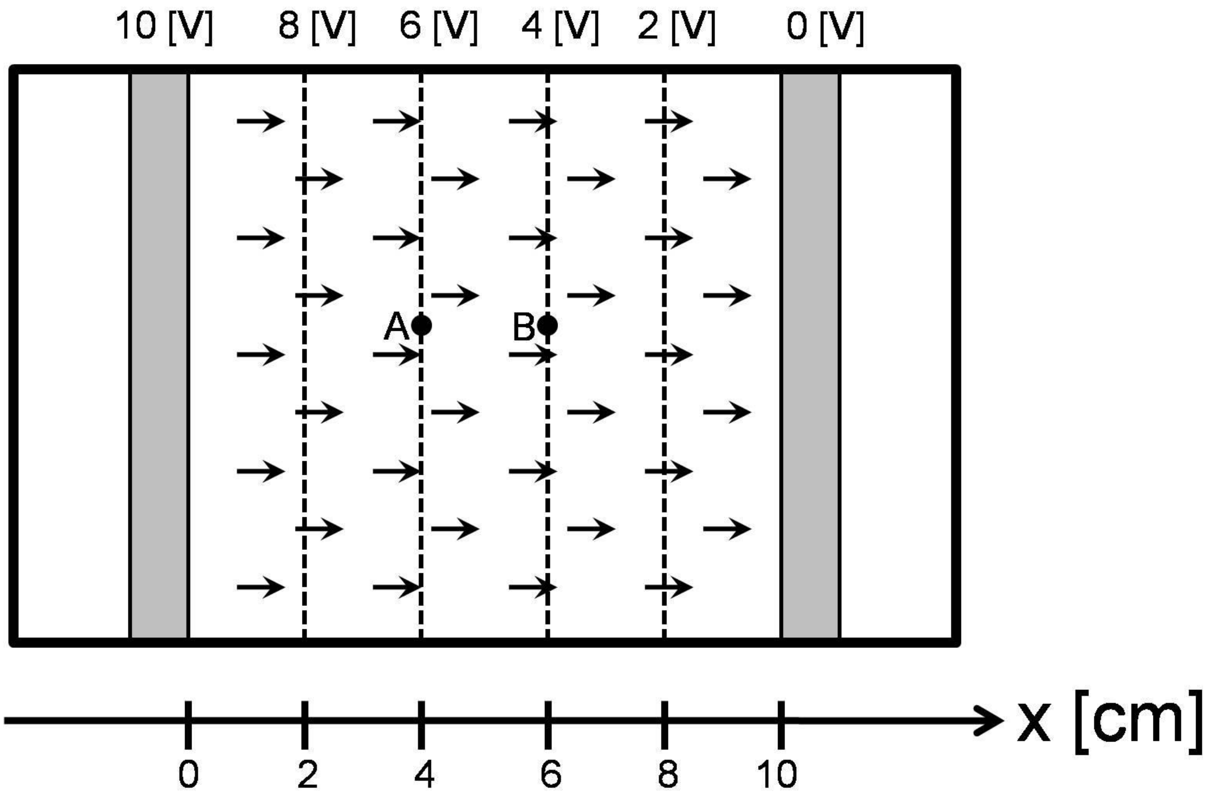
¿ **1-3**

In the following picture depicting equipotential lines (dashed lines of constant voltage), label in the picture where the two regions are located that have the strongest electric field and the two regions that have the weakest electric field. Use the letter 'S' for the region of strongest electric field and 'W' for the region of weakest electric field. Below the picture, explain how you made your decision. ***Draw on the picture below and write an explanation below the picture.***



Perhaps the simplest system to study is the conducting "parallel plates". Two parallel walls of a conductor are separated with each wall electrified with a different voltage. In the example below, the conducting plates are separated by 10 [cm] and given electric potentials of 10 [V] for the plate on the left and 0 [V] for the plate on the right. Note that since the voltage is constant throughout any part of a conductor, setting one part of the plate to 10 [V] means that any point on the conductor is at 10 [V] (and similarly for the plate set to 0 [V]).

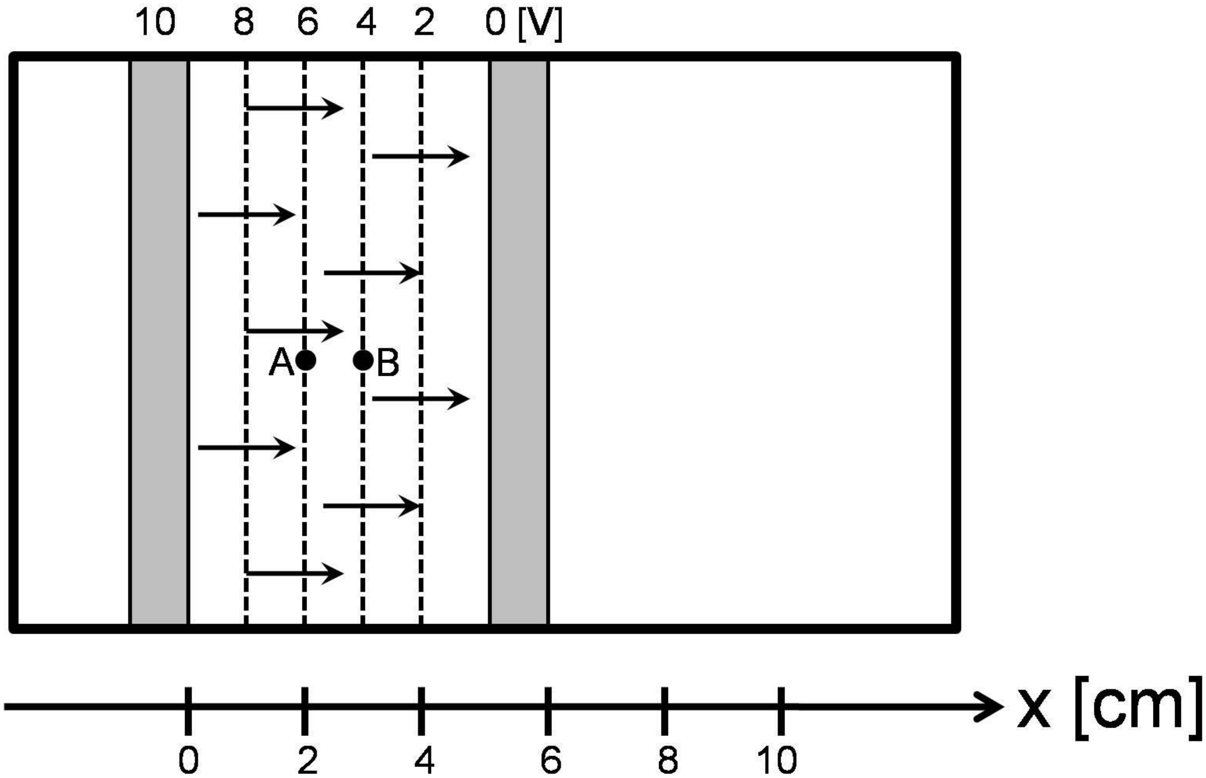
Four equipotential lines are shown between the plates as dotted lines. Note that they are parallel and equally spaced. The electric field points 'down the voltage hill' from left to right. Several arrows have been drawn to show the electric field. Note that they are all the same size and direction indicating that the electric field is *constant and uniform* between the conducting plates.



The electric field between the plates can be calculated using any two data points. Points at A and B have been chosen at random. The electric field calculated using these two points is (using meters for distance):

$$\vec{E} = \frac{-\Delta V}{\Delta d}\hat{x} = \frac{-(4-6)}{(0.06-0.04)}\hat{x} = \frac{2}{0.02}\hat{x} = 100\left[\frac{\text{V}}{\text{m}}\right]\hat{x}.$$

Now examine what happens when the distance between the plates is reduced by half:



The equipotentials are still parallel and equally spaced. The electric field is still constant and uniform between the plates, but the arrows are drawn twice as long to indicate that now the electric field is twice as large as before. Let's check this using the points A and B that have been shifted from their previous positions:

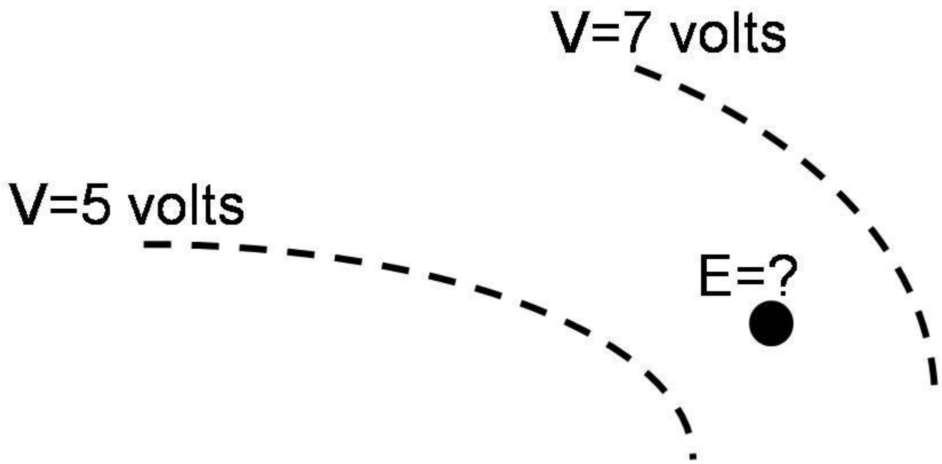
$$\vec{E} = \frac{-\Delta V}{\Delta d}\hat{x} = \frac{-(4-6)}{(0.03-0.02)}\hat{x} = \frac{2}{0.01}\hat{x} = 200\left[\frac{\text{V}}{\text{m}}\right]\hat{x}$$

¿ 1-4

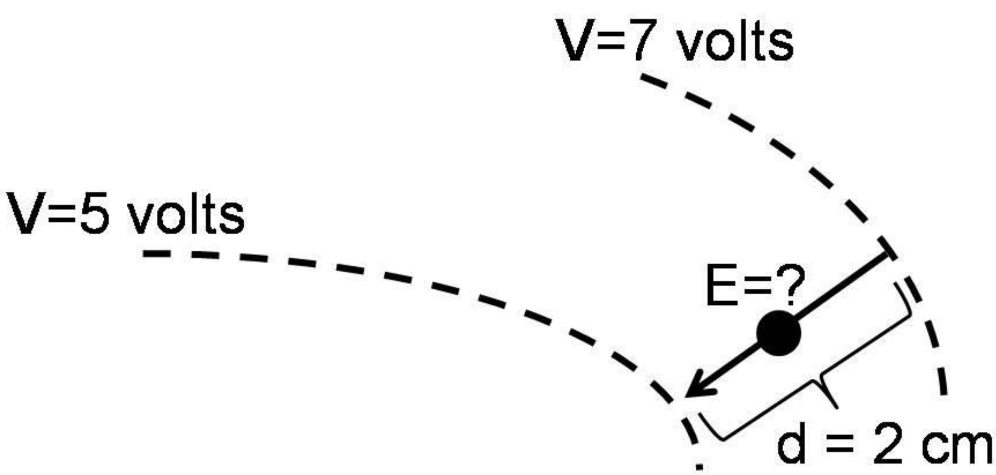
In each example, the plates are electrified with the same electric potential difference of 10 [V], and yet their electric field strengths are very different. Use the concept of "steepness of the voltage landscape" to explain the difference of these electric field strengths.

In the laboratory, we find is easiest to use a voltmeter to make measurements of the electric potential (using a DMM). However, this gives us values and not formulas for V so that we are not able to find **E** by taking partial derivatives of V. We must have a way of estimating **E** in the lab from voltage measurements. This technique will be illustrated using the following problem.

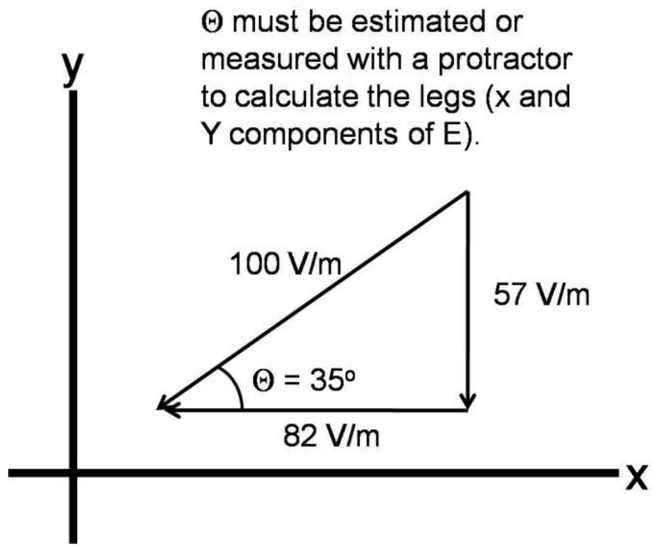
The following picture shows that a student has used a DMM to construct two equipotential voltage lines and wishes to find the electric field at some point between them.

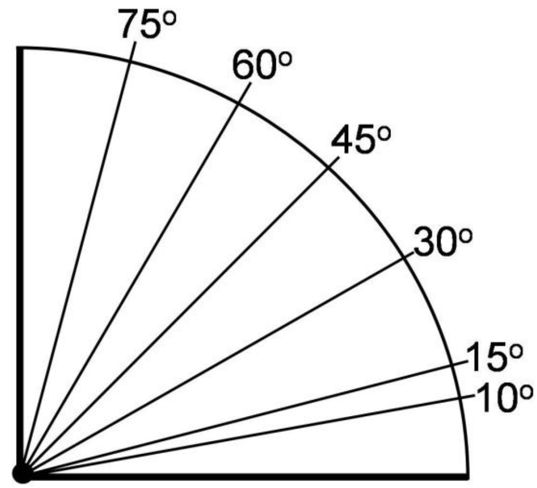


First, we draw an estimate of the best electric field line component that lies between the two equipotential lines (and measure its distance d):



Next we approximate the magnitude of E using differences in place of derivatives: $\left|\vec{E}\right| \approx \left|\frac{-\Delta V}{\Delta d}\right| = \frac{2}{0.02} = 100\left[\frac{\text{V}}{\text{m}}\right]$. This gives the magnitude (the size of the hypotenuse), and now we must break it up into components to get the electric field as a *vector*.

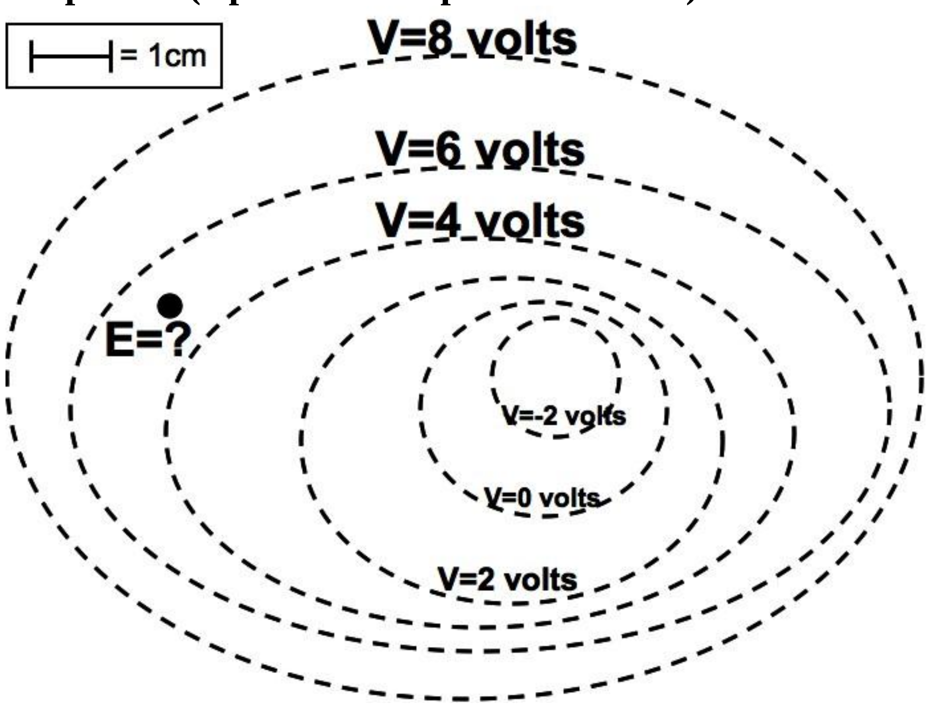




Now notice that for this particular coordinate system, the x component points in the negative direction along the x-axis and the y component points in the negative y-direction so that the final electric field vector is given by $\vec{E} = -82\hat{x} - 57\hat{y}\ \left[\frac{\text{V}}{\text{m}}\right]$.

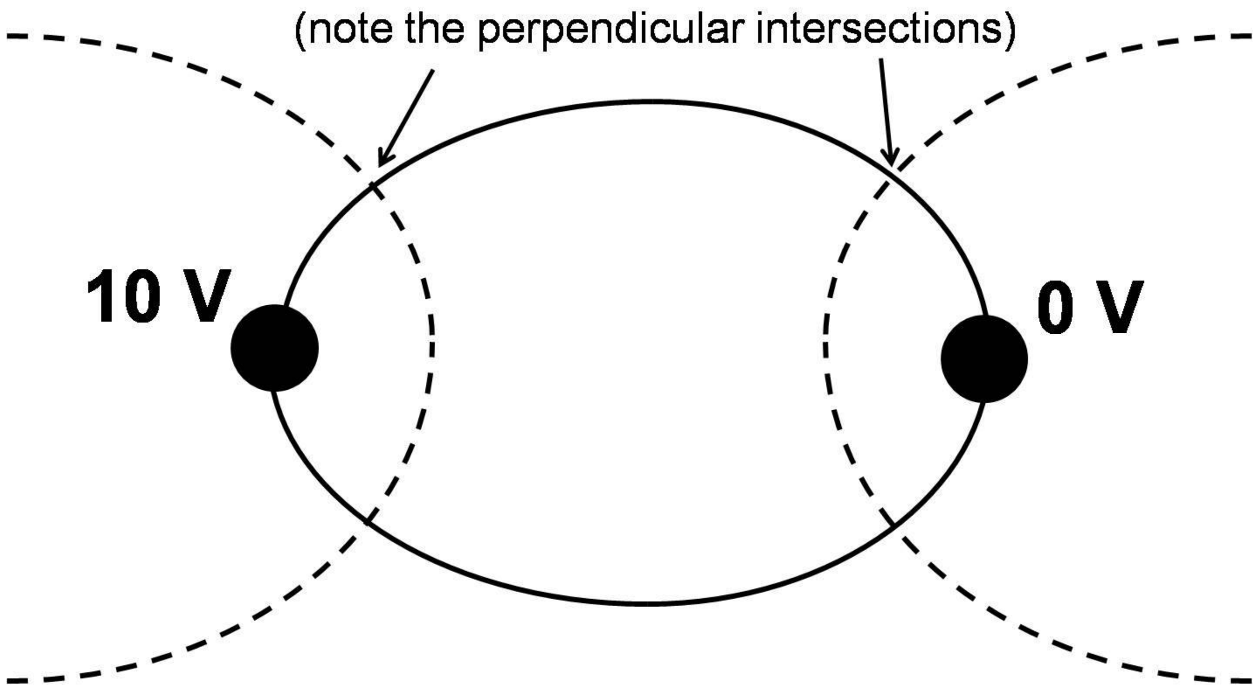
¿ 1-5

In the following picture depicting labeled equipotential lines, calculate the electric field at the marked point. Be sure to find E_X and E_Y, and write your final answer in vector notation. Show your calculations in the space next to the picture (a protractor is provided above).



Section 2: 2-D electric fields on conductive paper

! Do not write on the conductive paper, especially with pencil because the graphite conducts as well as the paper (and thus ruins it). Erase any pencil markings you see.



The above picture shows two point charges with 10 volts of electric potential difference between them. The dotted lines represent lines of constant voltage. For instance, all points on the dotted line to the left might be at 7 volts while all points on the dotted line on the right might be at 3 volts (as 10 volts decreases to 0 volts). A charge would not raise or lower its potential energy if it moved along a given dotted line because there would be no change in its potential energy. This means that there would be no force on the charge in the direction parallel to the dotted line. However, the charge would definitely change its electric potential (and thus its potential energy) if it moved off a dotted line. This means it feels an electric force pushing it away from (and perpendicular to) the dotted equipotential lines.

The solid lines represent electric field lines. They also show the direction of electric force that a charge would feel since $\vec{F} = q\vec{E}$. Note they are perpendicular to the equipotential lines where they intersect.

! Do not write on the conductive paper!

¿ 2-1

Electrify the dipole conductive paper (two dots of silver paint) with $\Delta V = 10\,\text{volts}$. Use a DMM to measure the locations of at least seven *dashed* equipotential lines and sketch them on special graph paper which matches the conductive paper. Be sure to use the physical symmetry of the system to reduce your work by 75%. Make a copy for both lab partners.

(answer on separate graph paper)

¿ 2-2

Sketch at least 8 electric field lines using *solid* lines on top of the dashed equipotential lines you just graphed. (Each partner should use their own copy for this.)

(answer on separate graph paper)

¿ 2-3

Label the part(s) of your sketch where the electric field appears to be the strongest. (Each partner should use their own copy for this.)

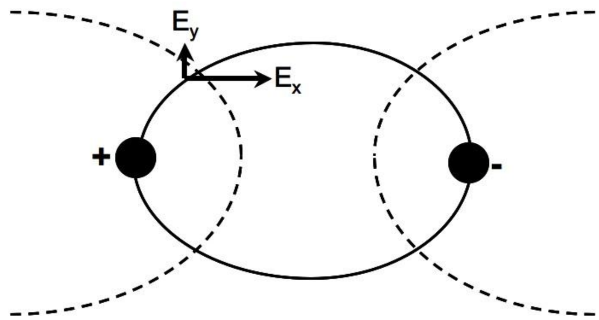
(answer on separate graph paper)

¿ 2-4

Calculate the electric field at the point that is 2 cm to the left and 3 cm above the center of the dipoles using the derivative approximation. Be sure to express your answer for the electric field in vector notation.

¿ **2-5**

Draw both electric field components for the point in the previous problem as arrows on your field mapping paper and label the strength of the field in each direction. ***At this point your field mapping paper should look something like this only with many more lines*****:**

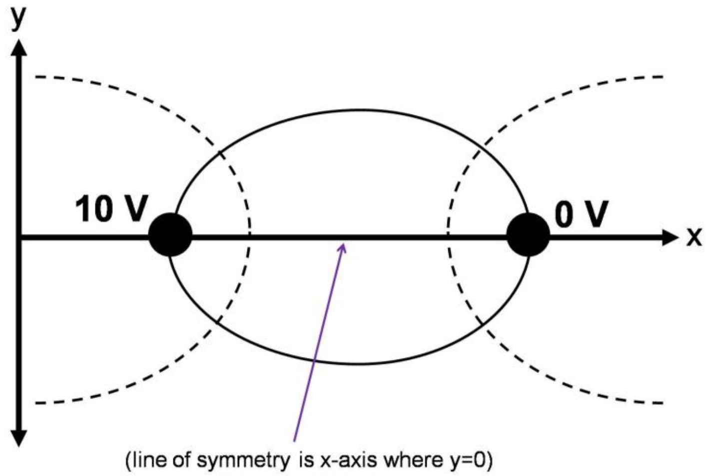


(answer on separate graph paper)

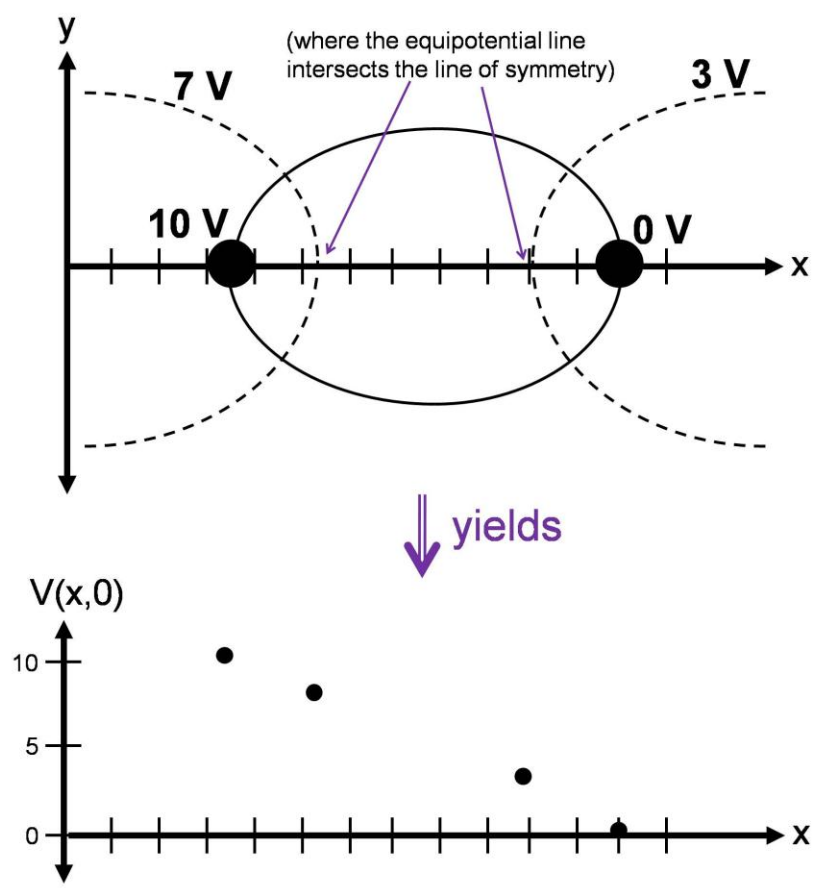
¿ **2-6**

Discuss where the electric field should be the strongest for the dipole system based upon the spacing of the equipotential lines.

¿ **2-7**



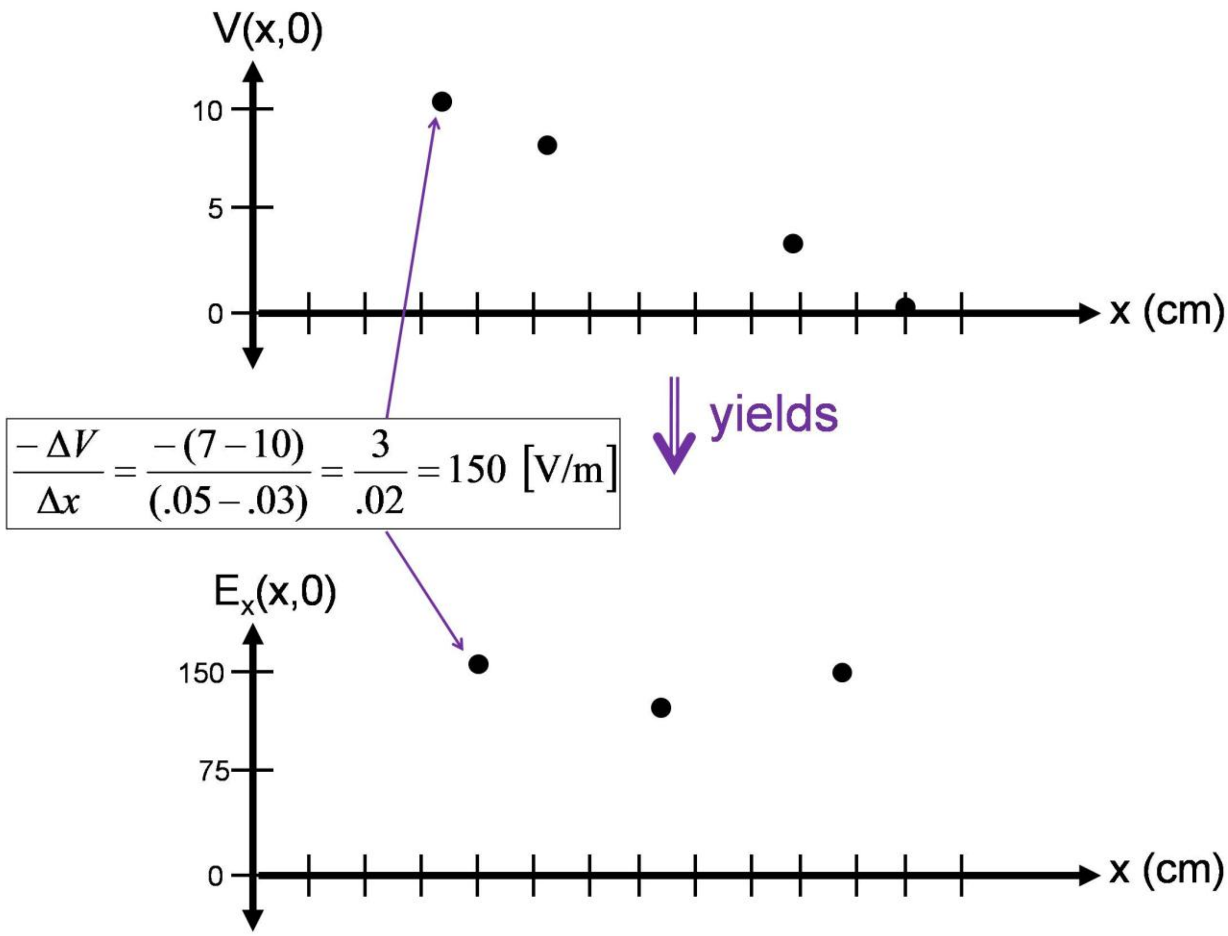
Place an x-y coordinate system on your graph paper as shown above. On another sheet of regular graph paper, graph voltage versus the x-coordinate (V(x,0) vs. x) along the line of symmetry that goes through both poles of the dipole conducting paper using your previous results. Your voltage axis and distance axis should be in SI units. An example is shown below. (answers on separate graph papers)



¿ 2-8

On another sheet of regular graph paper, use differences $\vec{E}_x \approx \frac{-\Delta V}{\Delta x}$ to approximate and graph $E_X(x,0)$ vs. x. Use your previous voltage graph along the line of symmetry (y=0). This requires calculating the electric field *in the x-direction only* for points along the line of symmetry, but this is alright since $E_y = 0$ along this line due to the symmetry of the system. Make a copy for both lab partners. An example is shown below.

(answer on separate graph paper)



Section 3: connecting the concepts of voltage and electric field

¿ 3-1

Find and draw the equipotential lines for the parallel plate conductive paper (two long bars of silver paint) and sketch them on graph paper using dashed lines. Find at least five equipotential lines between the plates. Be sure to find the potential in each region outside the parallel plates.

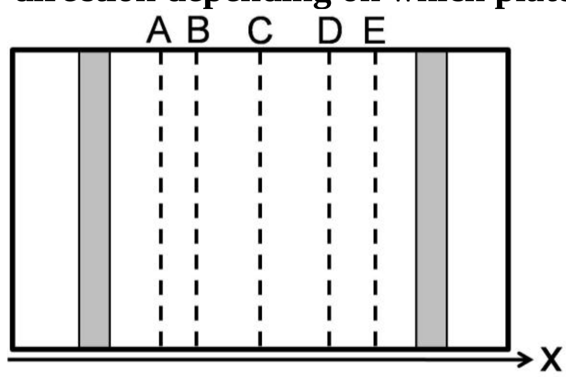
(This should take only a few minutes!)

Make a copy for both lab partners.

(answer on separate graph paper)

¿ 3-2

Fill in V and x in the below table using the data you just obtained. Compute ΔV and Δx, and use these to find the electric field (which may be in the positive or negative x-direction depending on which plate was grounded).



point	V	ΔV	x	Δx	E_x
A		----------		----------	----------
B					
C					
D					
E					

¿ 3-3

What do you notice about the strength of the electric field *everywhere* between the plates as well as outside the plates?

Section 4: exploring electric fields

¿ 4-1
Find a novel conducting paper of silver paint that looks interesting to you. Find and sketch its equipotential lines on graph paper using dashed lines.

(This should take only a few minutes, hurry up!)

Make a copy for both lab partners.

(answer on separate graph paper)

¿ 4-2
Sketch the electric field lines on your previous equipotential graph using solid lines.

(This should take only a few minutes, hurry up!)

(answer on separate graph paper)

Section 5: authentic assessment

(Students must be supplied with a strip of conductive paper 1 [cm] by 10 [cm] with alligator clips attached at either end.)

Find the average electric field strength <u>and direction</u> between two points of conductive paper 10 [cm] apart electrified by a 10 [volt] electric potential difference.

<u>Hint</u>: You may solve this problem *experimentally* by making measurements or *theoretically* by making a calculation. One method is **much** easier.

If you are uncomfortable having another student check your work, please ask your TA.

¿ 5-1

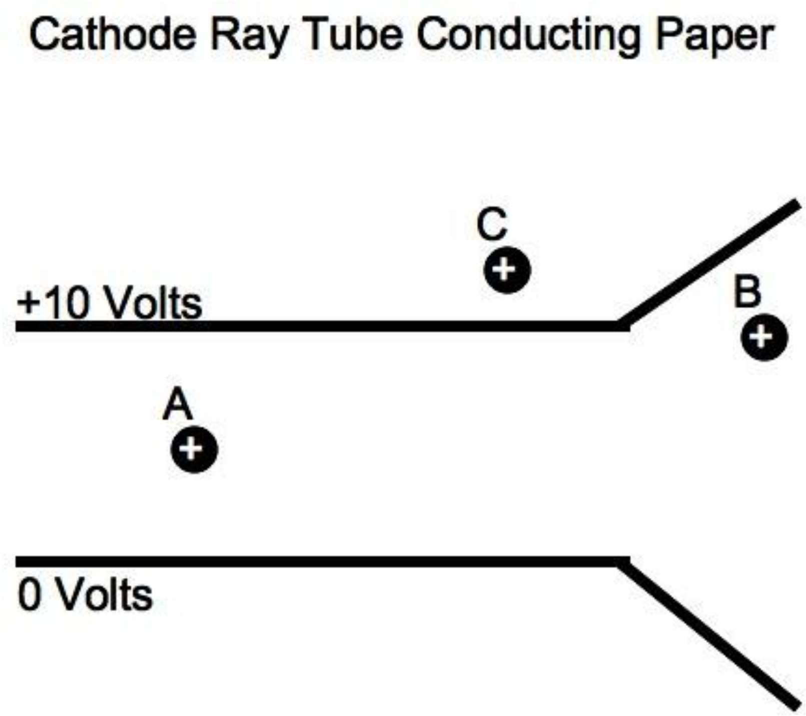
Show a student in a different group that you can successfully calculate the average electric field magnitude and direction between 10 [cm] of conducting paper electrified by 10 [volt]. Once you are successful, have them sign below. Note: if someone is stuck, please give them advice!

"Yes, I have seen this student theoretically calculate the electric field in a 10 [cm] strip of conductive paper with 10 [volt] across it. They understand how important it is to <u>think</u> about a physical situation before manipulating it!"

Student Signature:____

Section 6: open-ended

Use the cathode ray tube conductive paper (shown below) to find out what would happen to a positive test charge of +3.0 [nC] placed (initially at rest) at three unique locations on the conductive paper (points A, B, and C shown in the picture below). You must use the equation $\vec{F}_E = q\vec{E}$ and Newton's second law of motion to calculate the magnitude of the **acceleration** of the test charge if its mass was 10 [μg].



You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the next page.

¿ 6-1
hypothesizing/planning:

¿ 6-2
observations/data:

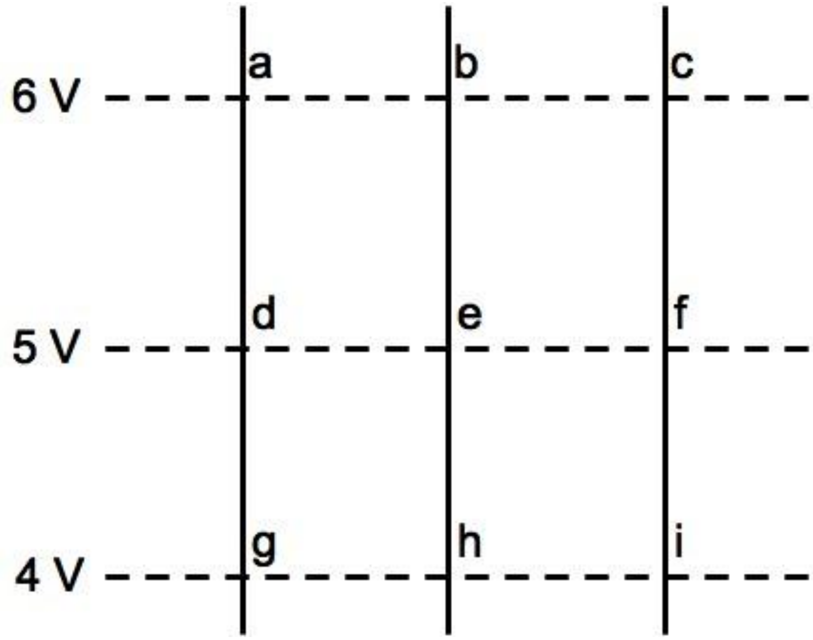
¿ 6-3
calculations/conclusion

I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: ____**

Week 3 Take-Home Quiz

Score:__________ /5



¿ THQ-1 (1-point)

Above is a sketch of some equipotential lines (dashed) and some electric field lines (solid). The points where these intersect are labeled. If an electron is released from rest at point *e*, which intersection will it reach some time later?

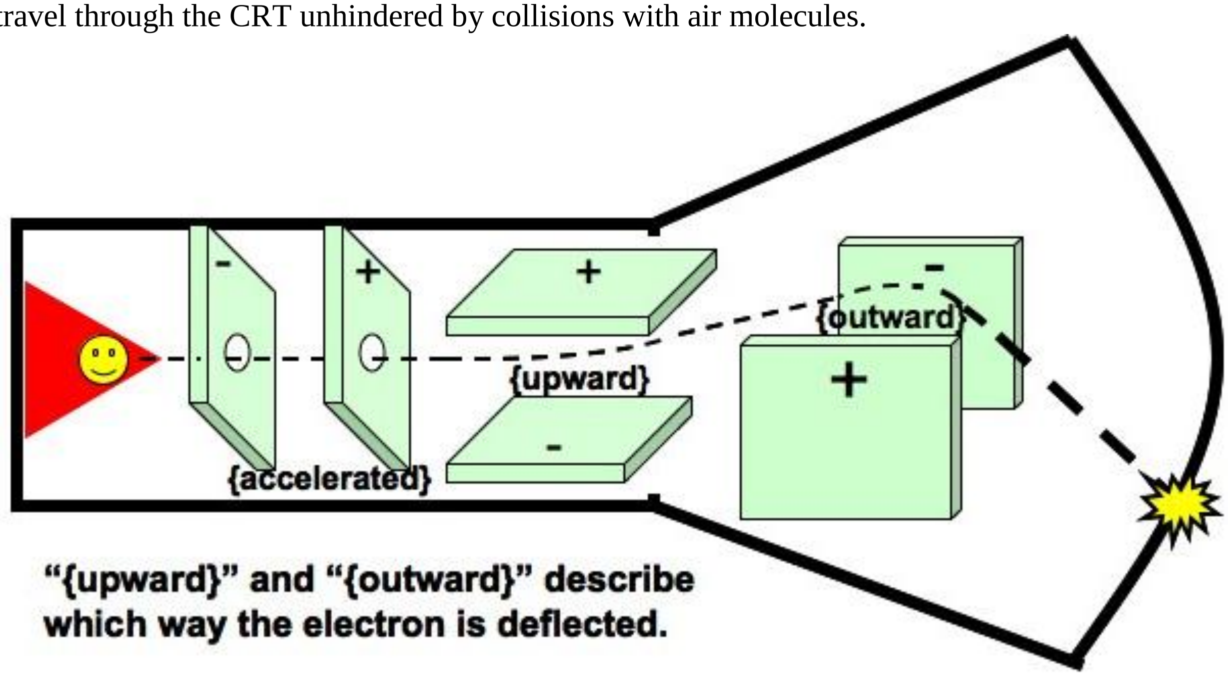
¿ THQ-2 (4-points)

Now calculate the velocity of the electron when it reaches that point. Hint: use energy conservation with $\Delta K = -\Delta U = -(q\Delta V) = -(-e\Delta V)$ **where** $K = \frac{1}{2}mv^2$**. Note:** $m_e = 9.1 \times 10^{-31}$ **kg.**

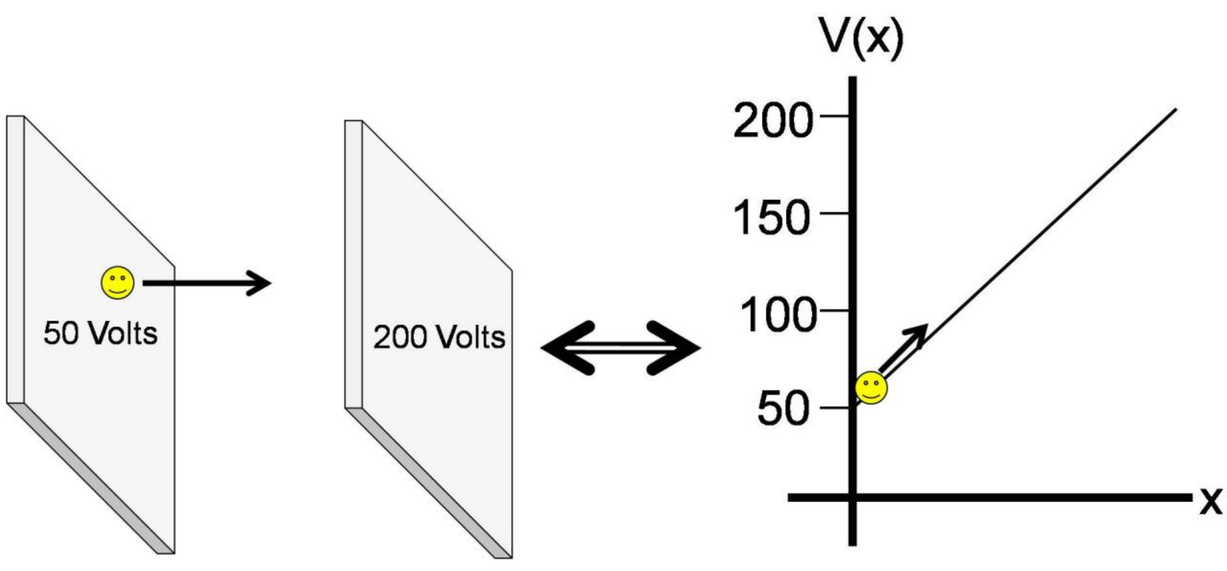
Week 4 Pre-Lab: Cathode Ray Tube

Read the following short pre-lab upon which you will take a quiz at the beginning of lab.

A cathode ray tube works by 'boiling' electrons off a cathode heating element and accelerating them with a large voltage difference. Then the high-speed electrons pass between a pair of charged deflection plates so that the path of the electron is altered. There are two pairs of deflection plates for vertical deflection and then horizontal deflection (see below figure). Finally, the electrons strike a screen coated with a fluorescent material and you see a scintillation take place (i.e. you see light emitted). All of this is done in a vacuum so that the electron can travel through the CRT unhindered by collisions with air molecules.



An electron moves from low to high voltage. An electron accelerated from 50 [V] to 200 [V] will experience a ΔV of +150 [V]:



The work done on a charged particle when moving between voltages is given by the formula:

$$W_{\substack{\text{done on}\\\text{object}}} = -q\Delta V \quad .$$

An electron has a charge of q = $-1.9\text{x}10^{-19}$ [coul] so that if an electron moves between two plates with ΔV = +150 [V], the electric field will do W = $+2.85\text{x}10^{-17}$ [J] of work on the electron.

The work-energy theorem states that

$$W_{\substack{\text{done on}\\\text{object}}} = \Delta K \quad ,$$

so this work done on the electron changes it's kinetic energy by K = $+2.85\text{x}10^{-17}$ [J]. If we assume the electron started at rest, and since an electron has a mass of $9.1\text{x}10^{-31}$ [kg],

$$\Delta K = \frac{1}{2} m\left(v_f^2 - 0^2\right) = 2.85\text{x}10^{-17}\ \text{[J]} \, .$$

Thus one may solve for the final velocity of the electron:

$$v_f = \sqrt{\frac{2\Delta K}{m}} = 8\text{x}10^{6}\ \text{[m/s]}$$

which is 3% the speed of light, roughly 15 million miles per hour.

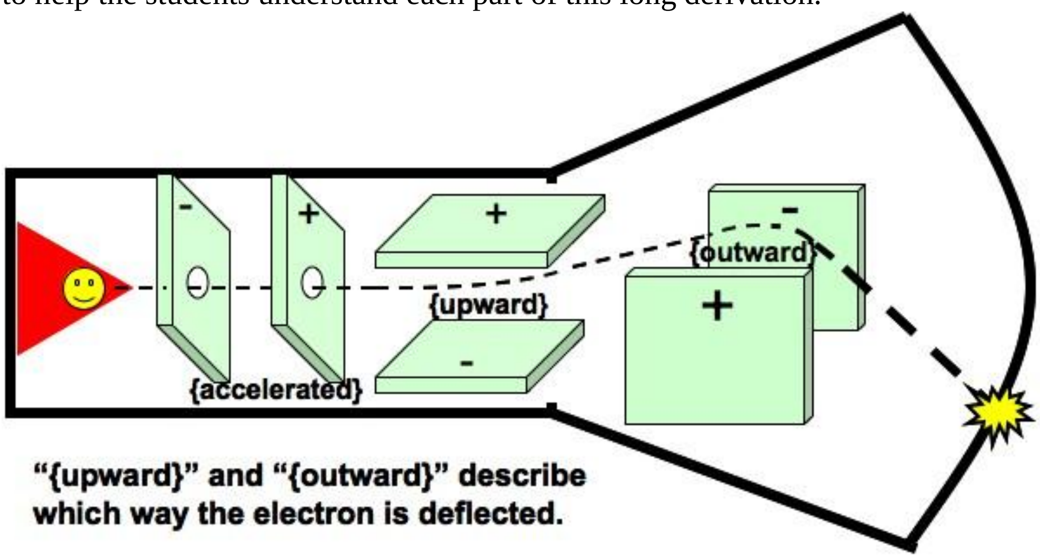
Week 4 Lab: Cathode Ray Tube

Students Absolutely Must Learn…

- How charged particles behave in a scalar electric potential field.
- How charged particles behave in an electric vector field.
- How to relate kinematics/mechanics concepts to electricity concepts.
- How a CRT works, how parallel plates of different voltages affect electrons.
- How to complete and explain a long physics derivation.

Section 1: cathode ray tube derivations

The operation of a cathode ray tube is described by just a few simple physics concepts. However, the chain of logic/math that relates the plate voltages to where the electron strikes the scintillation screen is quite cumbersome. Many student become confused in the derivation that calculates this deflection distance of the electron. Much of the theoretical work that follows is designed to help the students understand each part of this long derivation.



¿ 1-1

In the cathode ray tube, an electron is initially at rest (approximately) and is accelerated by a force produced by an electric field. However, in lab you will only know the positive change in voltage V_a (really "ΔV_a") of the plates through which the electron is accelerated. What *simple* formula using V_a, q and W (work) can you write to relate the work done on the electron to the change in voltage of the apparatus? Note the "V" is used for voltage and "v" for velocity. (*Check your answer with other students or your TA!*)

Your formula:

¿ 1-2

Now slightly extend this formula using the work-energy theorem. The work-energy theorem states that the change in kinetic energy is equal to the work done on the object. Using this concept, write a formula relating the change in the electron's kinetic energy to the accelerating voltage V_a of the apparatus (use V_a, q and ΔK). (*Be sure to check your answer with other students or your TA!*)

Your formula:

¿ 1-3

Write a formula that describes the final velocity of the electron if it starts from rest and you know the work done on the electron (use v_f, m_e, V_a, and q). (*Be sure to check your answer with other students or your TA!*)

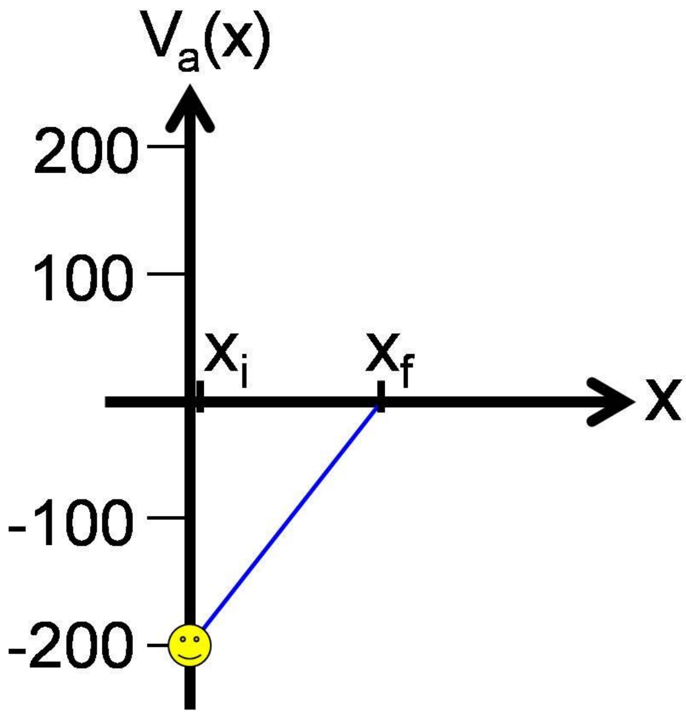
Your formula:

¿ 1-4

Explain what the sign of the accelerating voltage difference V_a must be in order for your formula in 1-A-2 to make sense? Reconcile this with your knowledge of how negatively charged particles respond to an electric field. Your explanation:

¿ 1-5

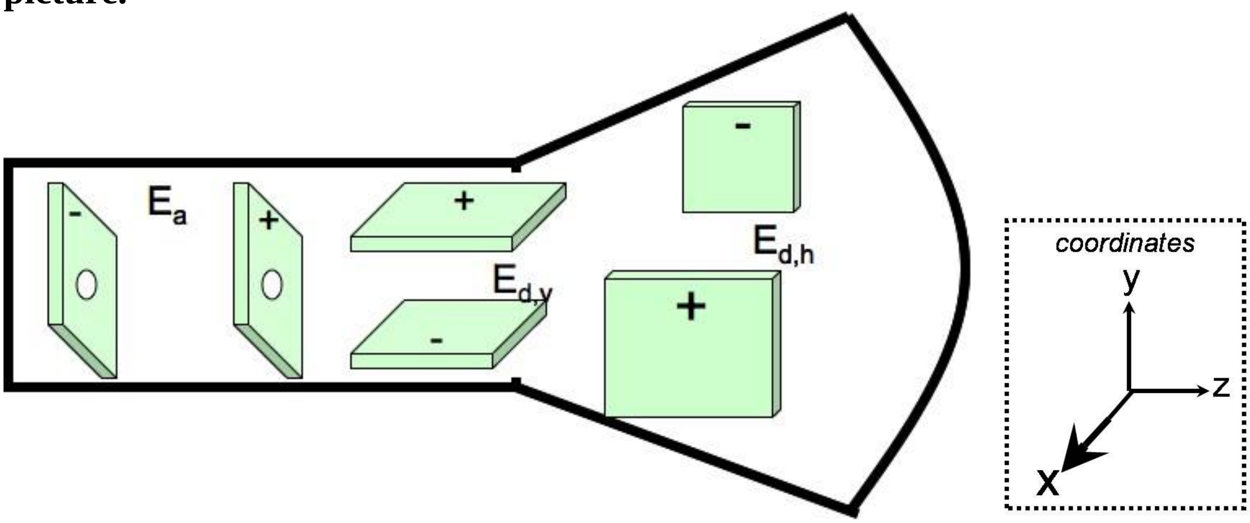
Now try out your formula using some numerical values. If the electron starts at the position x=0 on the following graph, find out the speed of the electron once it has reached the area of constant electric potential. (*Remember that electrons flow* *<u>upward</u>* *in the voltage landscape.*) You should use the electron charge, $q = -1.60 \times 10^{-19}$ C, and the electron mass, $m_e = 9.11 \times 10^{-31}$ kg. Your calculations and answer in SI units:



Now you know how to find speed of the electrons after they are initially accelerated, you will study how the electrons are deflected by the charged deflecting plates.

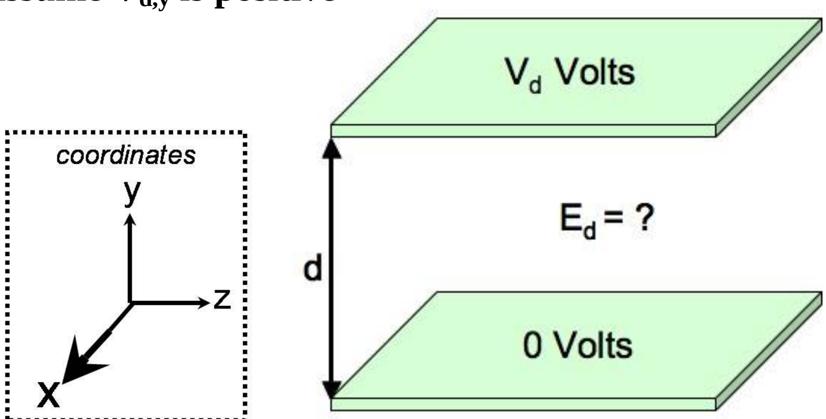
¿ 1-6

There are three electric fields affecting the trajectory of the electron. E_a accelerates the electron initially to a high speed. $E_{d,v}$ causes a deflection in the vertical direction and $E_{d,h}$ causes a deflection in the horizontal direction. In the CRT figure below, draw arrows correctly depicting the direction and magnitudes of these fields. Do you best to draw $E_{d,v}$ in the three-dimensional picture.



¿ 1-7

Now examine a pair of charged deflection plates (see figure). The voltage difference between the plates is $V_{d,y}$. Assume the plates are separated by a distance d. Assume $V_{d,y}$ is positive



¿ 1-8

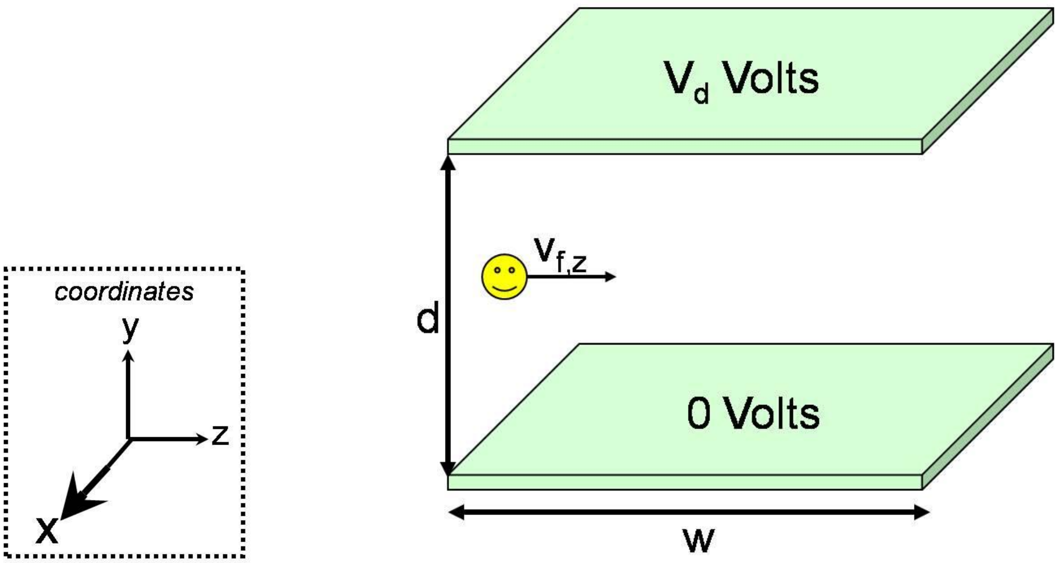
Find the magnitude and direction of the electric field between the plates E_y in terms of d and $V_{d,y}$ (ignore any edge effects). Your answer:

¿ 1-9

Determine the acceleration a_y felt by an electron inside the space between the plates using e, m_e and E_y. Your answer:

¿ 1-10

Now examine what happens when an electron enters the space between the vertical deflection plates (see figure).



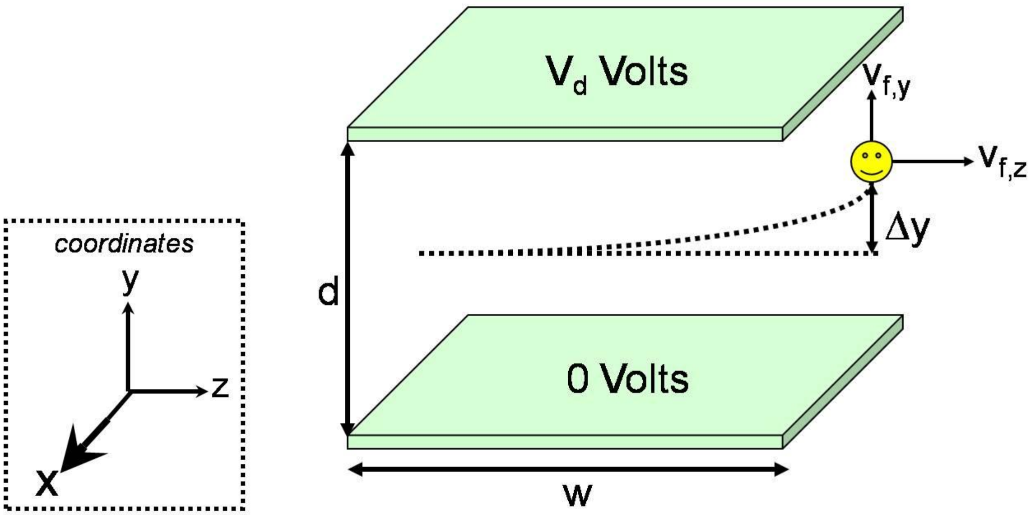
If the electron enters with a velocity in the z-direction of $v_{f,z}$ and travels the length of the plates w, how long does it take for the electron to reach the other side, Δt? Write your answer for Δt using w and $v_{f,z}$. Your work and answer:

¿ 1-11

Explain why this time Δt is not affected by the acceleration in the y-direction caused by the deflection plates? Your explanation:

¿ 1-12

As the electron traverses the space between the deflection plates, it is accelerated in the y-direction.

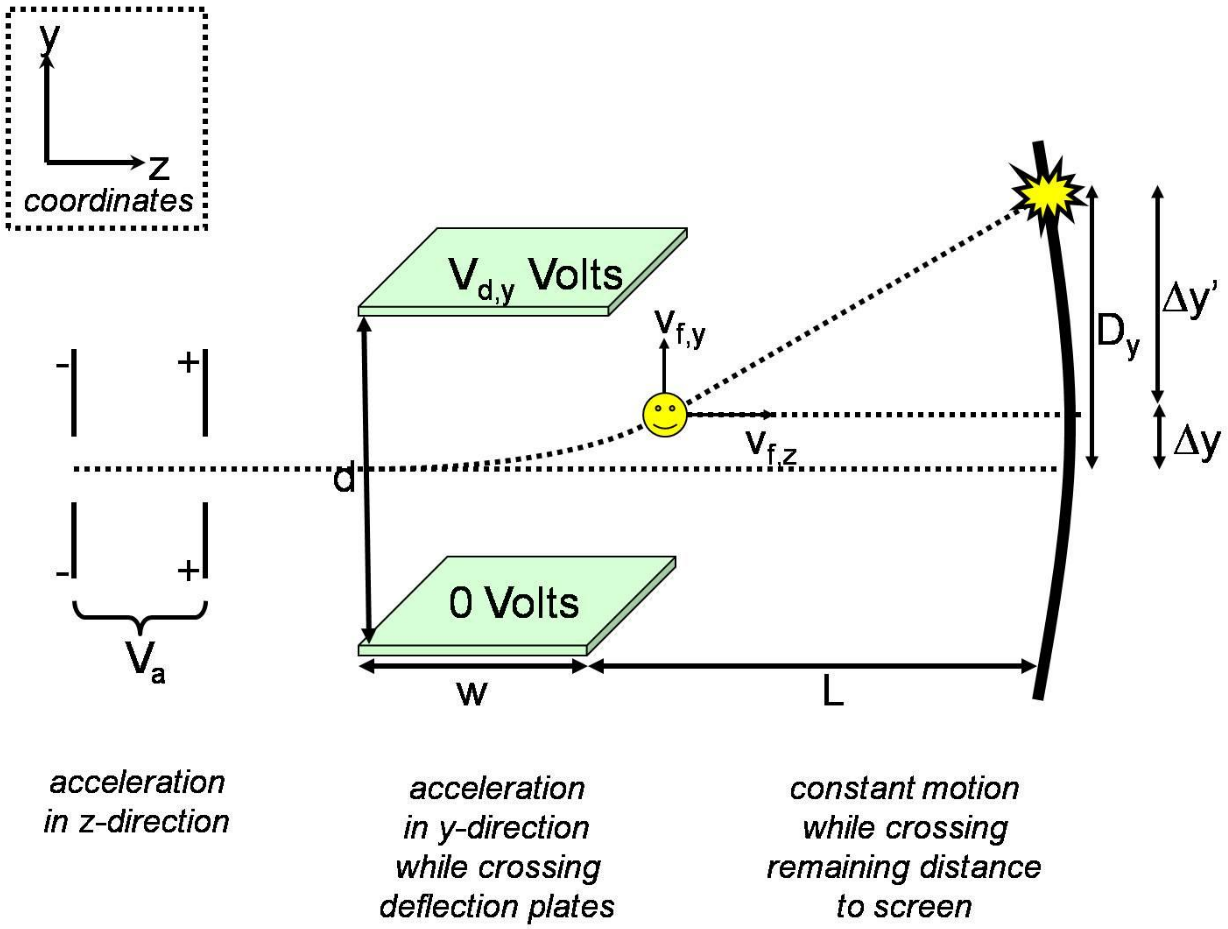


Using the kinematics equation $\Delta y = \frac{1}{2}\, a_y(\Delta t)^2$ to find vertical displacement Δy of the electron once it has reached the other side of the deflection plates. Write your answer for Δy using w, $v_{f,z}$, e, m_e and E_y. Your work and answer in SI units:

¿ 1-13

Use the kinematics equation $v_{f,y} = a_y(\Delta t)$ to determine the final y-velocity $v_{f,y}$ when the electron has reached the other side of the deflection plates. Write your answer for $v_{f,y}$ using w, $v_{f,z}$, e, m_e and E_y. Your work and answer:

The following is not a problem, but you must read through it in lab. This is where all the analysis you have done from the previous section is synthesized together to derive the *cathode ray tube equation*. **You will need to understand the following work in order to write your lab report.** The derivation will use the following figure to find $\mathbf{D_y}$.



¿ 1-14

READ THE FOLLOWING SENTENCE TWICE! Our goal here is to derive a final equation that relates D_y to the only things we can control in the lab V_a and $V_{d,y}$ (as well as the things we can't control: the geometric parameters of the CRT d, w and L). Note that capital V will always represent a voltage while a lower case v will always represent a velocity. In the derivation ignore directional negative signs for simplicity, and also we need to use $\frac{1}{2}m_e v_{f,z}^2 = e \cdot V_a$ (*usually to substitute for $v_{o,z}$*). Check here if you read that sentence twice:____

First we need to find $\mathbf{\Delta y}$: *(You will need to justify each step below in your lab report.)*

$$
\begin{aligned}
\Delta y &= \frac{1}{2} a_y (\Delta t)^2 \\
&= \frac{1}{2}\left(\frac{q \cdot E_y}{m_e}\right)\left(\frac{w}{v_{f,z}}\right)^2 \\
&= \frac{1}{2}\left(\frac{q\left(\frac{-V_{d,y}}{d}\right)}{m_e}\right)\left(\frac{w^2}{\left(\frac{2(-q)\cdot V_a}{m_e}\right)}\right) \\
&= \frac{1}{4}\frac{(-q)\cdot V_{d,y}\cdot w^2 \cdot m_e}{d \cdot m_e \cdot (-q)\cdot V_a} \\
&= \frac{w^2}{4d}\frac{V_{d,y}}{V_a}
\end{aligned}
$$

Next we need to find **Δy'**: *(You will need to justify each step below in your lab report.)*

$$
\begin{aligned}
\Delta y' &= v_{f,y}\Delta t' \\
&= (a_y \Delta t)\left(\frac{L}{v_{f,z}}\right) \\
&= \left(\frac{q \cdot E_y}{m_e}\cdot\frac{w}{v_{f,z}}\right)\left(\frac{L}{v_{f,z}}\right) \\
&= \left(\frac{q\left(\frac{-V_{d,y}}{d}\right)}{m_e}\cdot\frac{w}{v_{f,z}}\right)\left(\frac{L}{v_{f,z}}\right) \\
&= \frac{w \cdot L \cdot (-q)\cdot V_{d,y}}{d \cdot m_e v_{f,z}^2} \\
&= \frac{w \cdot L \cdot (-q)\cdot V_{d,y}}{2d \cdot (-q)\cdot V_a} \\
&= \frac{w \cdot L}{2d}\cdot\frac{V_{d,y}}{V_a}
\end{aligned}
$$

Finally this gives our equation for the total deflection on the oscilloscope screen $\mathbf{D_y}$: $D_y = \left(\frac{w^2}{4d} + \frac{w \cdot L}{2d}\right)\cdot\frac{V_{d,y}}{V_a}$. However, we cannot open up the CRT to measure **d**, **w** or **L** so we might as well replace all these geometric factors with a single unknown geometric constant $\mathbf{k_{g,y}}$: $D_y = k_{g,y}\frac{V_{d,y}}{V_a}$. THIS IS OUR FINAL CRT DEFLECTION EQUATION. Note that by

symmetry we get the same derivation for the total deflection in the horizontal x-direction: $D_x = k_{g,x} \frac{V_{d,x}}{V_a}$. THEREFORE, THERE IS A CRT DEFLECTION EQUATION FOR EACH DEFLECTION DIRECTION EACH WITH ITS OWN GEOMETRIC CONSTANT.

¿ 1-15

Explain how we have we achieved the goal set out in 1-14?

Subsection D

Now you need to answer some questions about the CRT deflection equations.

¿ 1-16

Given the CRT deflection equation in the vertical direction $D_y = k_{g,y} \frac{V_{d,y}}{V_a}$, what you would see on the CRT screen if the deflection voltage was increased. Explain why this would happen using a physical argument (i.e. not using math). Your answer and explanation:

¿ 1-17

Given the CRT deflection equation in the vertical direction $D_y = k_{g,y} \frac{V_{d,y}}{V_a}$, what you would see on the CRT screen if the accelerating voltage was increased. Explain why this would happen using a physical argument (i.e. not using math). Your answer and explanation:

Section 2: testing the cathode ray tube equations

You will now ***experimentally test*** the horizontal CRT deflection equation $D_x = k_{g,x}\frac{V_{d,x}}{V_a}$ by adjusting $\mathbf{V_{d,x}}$ and observing $\mathbf{D_x}$. If all goes well, you will be able to find an experimental value for the x-geometrical constant without breaking the CRT open to measure it by hand.

¿ 2-1

Use tape on screen to mark position of electron beam when there is NO DEFLECTION ($V_{d,x}$ set to zero to find the 'origin' of the CRT). Be sure to record V_a and keep this value constant for the rest of this section. (V_a is the sum of V_B and V_C on the CRT power module and should be set as high as possible while the scintillation dot is still in focus). Record your constant accelerating voltage V_a:

¿ 2-2

Adjust $V_{d,x}$ on the horizontal plates and mark D_x on the tape for several values of $V_{d,x}$ (make a data table with at least 5 data points). Record your data table of $V_{d,x}$ and D_x:

¿ 2-3

Create graph of D_x vs $V_{d,x}$ by hand. Graph D_x vs $V_{d,x}$ on graph paper. Your data should give you a straight line.

¿ 2-4

Measure the slope of the line of best fit. Since $D_x = k_{g,x}\frac{V_{d,x}}{V_a}$, the slope will equal $\frac{k_{g,x}}{V_a}$ so multiply by V_a to obtain $k_{g,x}$. Record your result for $k_{g,x}$ here in SI units:

You will now ***experimentally test*** the vertical CRT deflection equation $D_y = k_{g,y}\frac{V_{d,y}}{V_a}$ that you have derived by adjusting $\mathbf{V_{d,y}}$ and observing $\mathbf{D_y}$. in order to estimate the y-geometrical factor. The y-geometrical constant in this other direction is different from z because the geometry of the deflecting plates is different in the z-direction from the y-direction, i.e. one set of plates is closer to the screen than the other.

¿ 2-5

Use tape on screen to mark position of electron beam when there is NO DEFLECTION ($V_{d,y}$ set to zero to find the 'origin' of the CRT). Be sure to record V_a and keep this value constant for the rest of this section. (V_a is the sum of V_B and V_C on the CRT power module and should be set as high as possible while the scintillation dot is still in focus). Record your constant accelerating voltage:

¿ 2-6

Adjust $V_{d,y}$ on the horizontal plates and mark D_y on the tape for several values of $V_{d,y}$ (make a data table with at least 5 data points). Record your data table of $V_{d,y}$ and D_y:

¿ 2-7

Create graph of D_y vs $V_{d,y}$ by hand. Graph D_y vs $V_{d,y}$ on graph paper. Your data should give you a straight line.

¿ 2-8

Measure the slope of the line of best fit. Since $D_y = k_{g,y}\frac{V_{d,y}}{V_a}$, the slope will equal $\frac{k_{g,y}}{V_a}$ so multiply by V_a to obtain $k_{g,y}$. Record your result for $k_{g,y}$ here in SI units:

You will now ***experimentally test in another way*** the horizontal CRT deflection equation $D_x = k_{g,x}\frac{V_{d,x}}{V_a}$ by adjusting $\mathbf{V_a}$ and observing $\mathbf{D_x}$.

¿ 2-9

Set V_a to about ½ to ¾ its maximum value and adjust $V_{d,x}$ to the largest value possible that still enables you to see the scintillation dot (it may be fuzzy, but you should measure deflections using the center of the dot). Be sure to record $V_{d,x}$ and to keep this value constant for the remainder of this section. Record your constant deflecting voltage $V_{d,x}$:

¿ 2-10

Adjust V_a to larger and larger values and record the corresponding horizontal screen displacement D_x for several values of V_a (make a data table with at least 5 data points). Record your data table of V_a and D_x:

¿ 2-11

Linearize your data by making a graph of D_x vs $1/V_a$ by hand. Graph D_x vs $1/V_a$ on graph paper. Your data should give you a straight line.

¿ 2-12

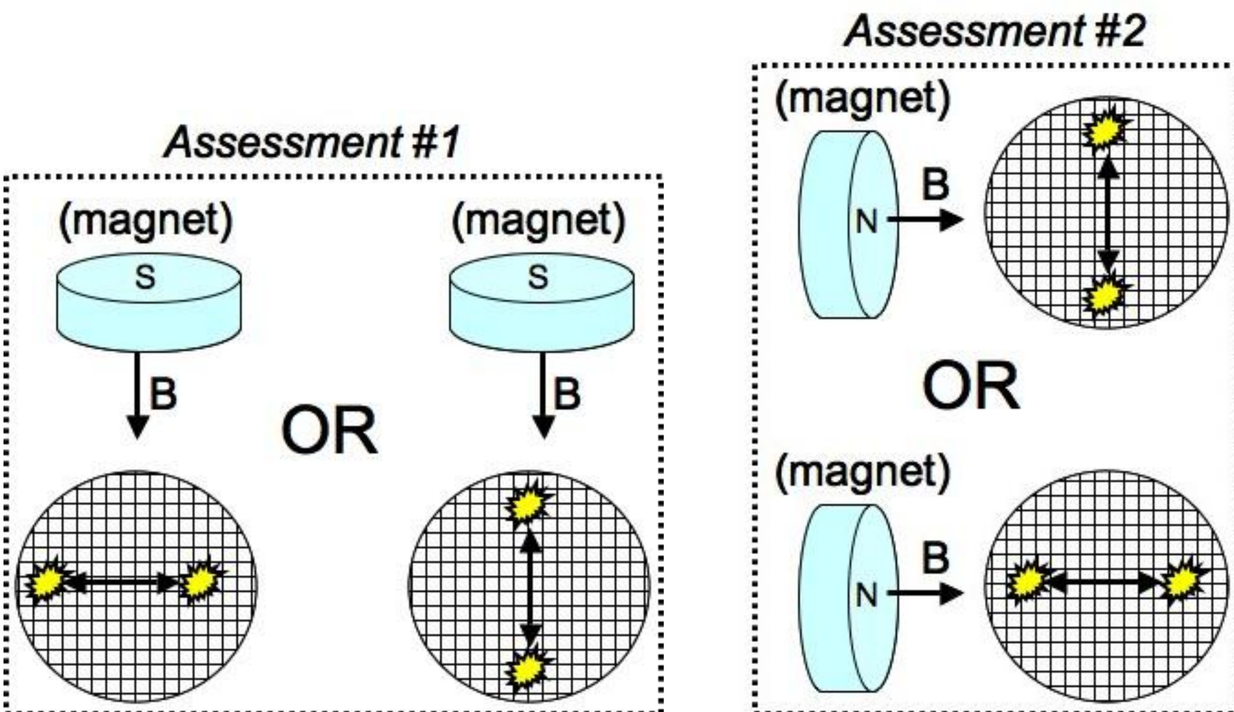
Measure the slope of the line of best fit. Since $D_x = k_{g,x}\frac{V_{d,x}}{V_a}$, the slope will equal $k_{g,x}V_{d,x}$ so divide by $V_{d,x}$ to obtain $k_{g,x}$. Record your result for $k_{g,x}$ here in SI units.

Section 3: authentic assessment

¿ 3-1

You will learn later that the magnetic force is given by $\vec{F}_M = q\vec{v} \times \vec{B}$, but usually the speed of the charged particle is too slow to be able to visually see the effects of the magnetic force. However, electrons in CRTs move so fast, you can actually see them being deflected by a magnetic field. In fact, this is how old-fashioned "television" first worked. You must correctly predict whether the scintillation dot will be deflected horizontally or vertically when a magnetic field is created nearby the CRT. Then check your prediction. For this you will need to remember what the cross product means in the Lorenz force equation (better ask around if you don't ☺), $\vec{F}_M = q\vec{v} \times \vec{B}$ and how to use the right-hand rule.

Circle your predictions then check them experimentally while showing a student in a different group:



"Yes, I have seen this student determine how magnetic fields affect moving electrons. They will be able to protect themselves from dangerous ions on their trip to Mars (if they take a magnet)!"

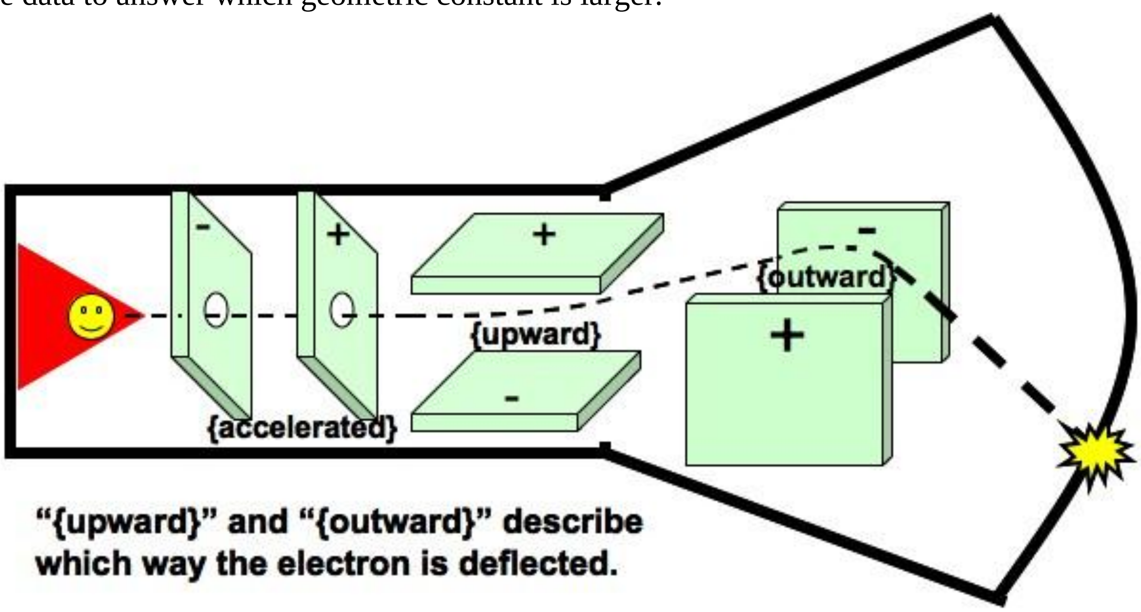
If you are uncomfortable having another student check your work, please ask your TA.

Student Signature:____

Section 4: open-ended

If you were able to see inside a CRT, you would see that one set of deflection plates is closer to the scintillation screen than the other set of deflection plates. If both pairs of deflection plates were identically shaped, then the pair closer to the screen would have a smaller **L** and therefore a smaller geometric constant $\mathbf{k_g}$. Your job is to determine whether the vertical plates or the horizontal plates inside your CRT are closer to the scintillation screen (assuming both pairs of plates are identically shaped). This is equivalent to finding which geometric constant is larger, $\mathbf{k_{g,x}}$ or $\mathbf{k_{g,y}}$.

You might say that you already know the answer to this based on your previous work. However, do not use previous results to answer the question, but instead think of an easier way to determine which geometric constant is larger. Here is a hint: given a certain deflection voltage, which direction seems to "use" that deflection voltage more. You should need to collect very little data to answer which geometric constant is larger.



You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

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Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the next page.

¿ 4-1
hypothesizing/planning:

¿ 4-2
observations/data:

¿ 4-3
calculations/conclusion

I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: ____**

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Week 4 Take-Home Quiz

Score:__________ /5

¿ THQ-1 (5-points)

Derive the CRT deflection equation. Clearly explain every step of the derivation in words (i.e. explain why one step of the equation is equal to the next which might be mathematical or based on physics concepts). You will not get credit for simply copying equations without demonstrating you understand the math and physics that connect all the steps.

(keep going…)

Unit 3 Lab Report Instructions

Unit Lab Report [40 points]

Use the following section titles in your report. Images, text or equations plagiarized from the internet are not allowed! Remember to write your report *alone* as collaborating with a lab partner will make you both guilty of plagiarism. **Please label your lab report sections:**

- **Title [0 points]** – A catchy title worth zero points so make it unique and fun.
- **Mini-Report [10 points]:** ***{4-6 paragraphs, ~2 double-spaced pages}***
  Choose **one** of the following sections about which to write your mini-report:
  Week 5 Section 3 or Week 6 Section 3
  Write a "mini-report" for one particular section of the lab manual. Describe what you did succinctly, and then what you found accurately. Then explain what the result means and how it relates to some of the concepts in the previous section. *You must write using sentences & paragraphs; bulleted lists are unacceptable.* ***Please label your mini-report sections:***
  - **Abstract:** Write 2-3 sentences about the goals of this section. Describe the concepts you were investigating and how the experimentation you performed allowed you to investigate these concepts. Write 2-3 sentences summarizing the procedure. Write 2-3 sentences summarizing the results and what the results mean with regard to the concepts you were investigating. *It is best to write the abstract last*.
  - **Procedure:** Do not provide a lot of specific details, but rather you should summarize the procedure so that a student who took the course a few years ago would understand what you did.
  - **Results:** Provide a description of the data you obtained such as data tables. Restate any measured values, calculated slopes of lines-of-best-fit, etc. Do not *interpret* your results, save any interpretation for the discussion.
  - **Discussion:** Analyze and interpret the results you observed/measured in terms of some of the concepts and equations of this unit. It is all right to sound repetitive with other parts of the report.
- **Open-Ended Discussion [10 points]** – ***{1-2 paragraphs, ~1 page double-spaced}*** Choose **one** of the open-ended experiments from the two weekly activities to write about. Describe your experimental goal and the question you were trying to answer. Explain the ideas you came up with and what you tried. If your attempts were successful, explain your results. If your attempts resulted in failure, explain what went wrong and what you would do differently in the future. *You must write using sentences & paragraphs; bulleted lists are unacceptable.*
- **Graphs [5 points] - {attach to your typed report}** Graphs must be neatly hand-drawn <u>during lab</u> on graph paper. Your graphs must fill the entire page (requires planning ahead), include a descriptive title, labeled axes, numeric tic marks on the axes, and unit labels on the axes. If instructed to calculate the slope of the line-of-best-fit, write it directly on the graph.
  Week 5: 1-2, 1-3
  Week 6: 3-5 (two graphs)
- **Take-Home Quizzes [2x5 points = 10 points] - {attach after your Graphs}**
- **Selected Worksheet Pages [5 points] - {attach after your Take-Home Quizzes }**
  Your TA will choose which pages you need to hand in.

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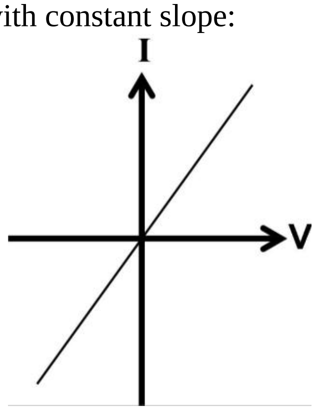
Week 5 Pre-Lab: Vulture Iguana Rabbit

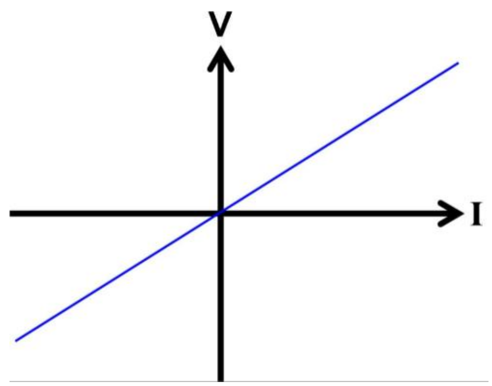
The resistance of a circuit component is the voltage drop across the component divided by the current flowing through the component, $R \equiv \frac{V}{I}$. If a circuit component has a high resistance, it will require a larger applied voltage to obtain a desired current through the component. Note that even though a 12 [V] car battery can deliver a great deal of power, it will not light a household light bulb which has a high resistance designed for the much higher 120 [V] household voltages.

Imagine you are in the desert and there is a vulture flying in the sky and a rabbit and an iguana walking on the ground. The rabbit sees the vulture flying over the iguana! This is a pneumonic device to remember the definition of resistance: $R = \frac{V}{I} \Rightarrow \text{Rabbit sees } \frac{\text{Vulture}}{\text{Iguana}}$. Of course the vulture sees the iguana on the ground with the rabbit: $V = IR$ and the iguana sees the vulture flying over the rabbit: $I = \frac{V}{R}$. Please never get these equations wrong on a test.

For an ohmic resistor, the equation $R_{\substack{\text{constant}\\\text{for ohmic}}} = \frac{\Delta V}{I}$ implies the resistance is the same value no matter what voltage is applied, and the current changes with voltage to keep the ratio $\frac{\Delta V}{I}$ constant. It should be noted that resistance of a material often depends on its temperature. Since a light bulb gets hotter as more voltage is applied across it, the light bulb's resistance grows with its brightness. So a light bulb definitely is non-ohmic.

Ohmic resistors have a constant ratio of current to voltage so data collected at different applied voltages (or different applied currents depending on how you run your experiment) will provide lines with constant slope:



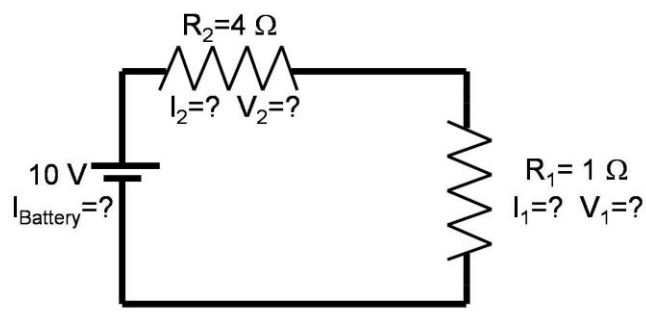


Real batteries have internal resistances that affect their performance by decreasing their effective voltage. For example, if you take a 1.5 V battery and attach a 0.000001 ohm resistor (like a wire), you will NOT obtain a 1,500,000 amp current! As the battery tries to supply a large current, it will heat up and its internal resistance will grow thereby lowering the voltage supplied to the resistor until only a small voltage is actually applied to the resistor. So if your 12 [V] car battery dies unexpectedly, you can't substitute your car battery with eight 1.5 [V] batteries in series even though they provide 12 [V] in series because their internal resistance will not allow them to deliver such a large current to move the engine's heavy parts.

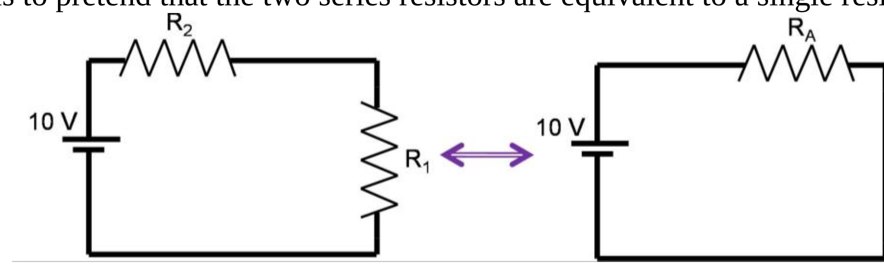
When two resistors are put into series, it is often useful to treat them as a single composite resistor and find the equivalent resistance of this single resistor. The formula for this is $R_{\text{equivalent}} = R_1 + R_2$.

When two resistors are put into parallel, the equivalent resistance is given by $R_{\text{equivalent}} = \dfrac{R_1 R_2}{R_1 + R_2}$.

Solving compound circuits is a very important skill. Here is an example where you must solve for the current through the battery I_{Battery}, the total resistance R_{total} as well as the voltages across and currents through each of the components:



The strategy is to pretend that the two series resistors are equivalent to a single resistor:



First collapse the two series components: $R_{\text{A}} = R_1 + R_2 = 5\ [\Omega]$. Since this is actually the total resistance of the circuit (assuming an ideal battery which has zero internal resistance), you may use Ohm's law to find the total current: $I_{\text{Battery}} = \dfrac{V_{\text{Battery}}}{R_{\text{A}}} = 2\ [\text{A}]$. Since charge cannot pile up anywhere in a circuit, this is also the same current as in R_1 and R_2: $I_1 = I_2 = 2\ [\text{A}]$. You can now find the voltage across R_1: $V_1 = R_1 I_1 = 2\ [\text{V}]$ and R_2: $V_2 = R_2 I_2 = 8\ [\text{V}]$. Due to the conservation of energy, you expect the voltages across the components to add to the total supplied by the battery and indeed 2+8=10.

Week 5 Lab: Vulture Iguana Rabbit

Students Absolutely Must Learn…

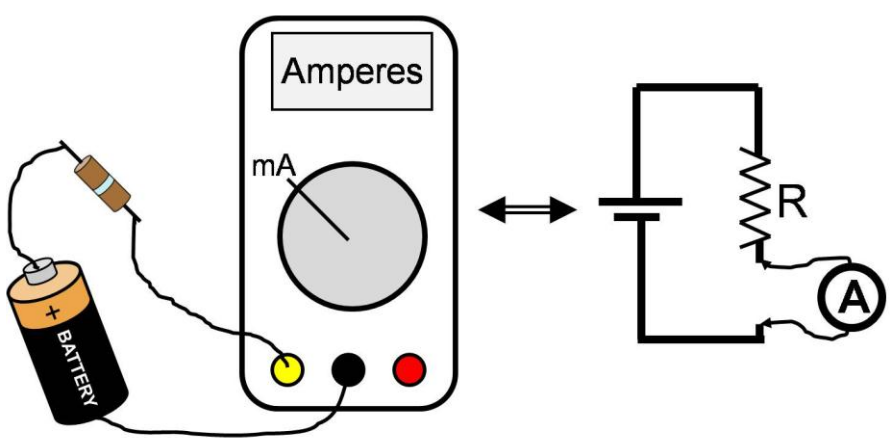
- How resistance R is defined whether or not a component is ohmic.
- How R, V and I are related in ohmic devices.
- How to find equivalent resistances in series and parallel.
- How to find equivalent resistances of complex compound circuits.
- How to use ohms law to find voltages and currents for all parts of a circuit.
- How to make an ammeter measurement.

Section 1: experimentally determining resistance

¿ 1-1

Make a sketch of the small board of resistors provided to you and use your DMM to measure the resistance of each (do this quickly, please). Label the values on your sketch.

The picture below is provided to remind you that to measure current, you must divert the charges flowing in the circuit *through* the DMM so that it may "count" them as pass through.



! Never apply such a large voltage that the resistor becomes very hot, dangerous and non-ohmic.

¿ 1-2

Experimentally verify that the 100 [Ω] resistor on your resistor board is ohmic at room temperature. Do this by gathering (voltage, current) data and making the appropriate graph. Your graph of your data should quite nicely show the linear behavior of your ohmic resistor. The correct choice of (V vs. I) or (I vs. V) should give your resistance as the slope and thereby check its experimentally measured resistance (see how close you got with your DMM, redo if bad).

(write data here and plot graph on separate graph paper)

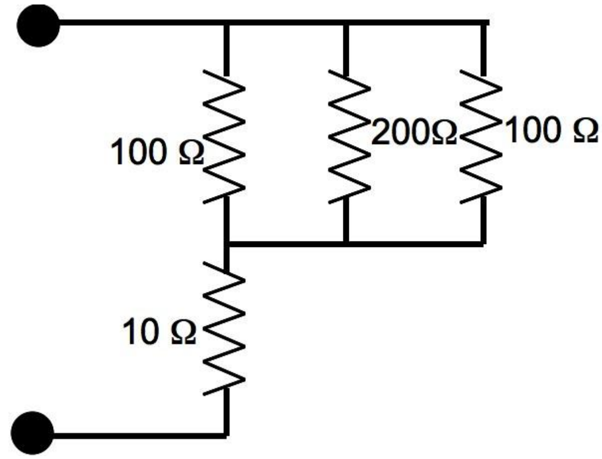
¿ 1-3

Experimentally verify that the 100 [Ω] resistor and the 200 [Ω] resistor in series produce an equivalent resistance of 300 [Ω] by taking (voltage, current) data and making the appropriate graph. Your voltage data should be gathered from across *both* resistors simultaneously since you want to treat them as a single resistor and find their equivalent resistance. Remember that the current is the same through both resistors.

! Do not apply such a large voltage that the resistor becomes very hot, dangerous and non-ohmic.

(write data here and plot graph on separate graph paper)

Section 2: compound circuits



¿ **2-1**

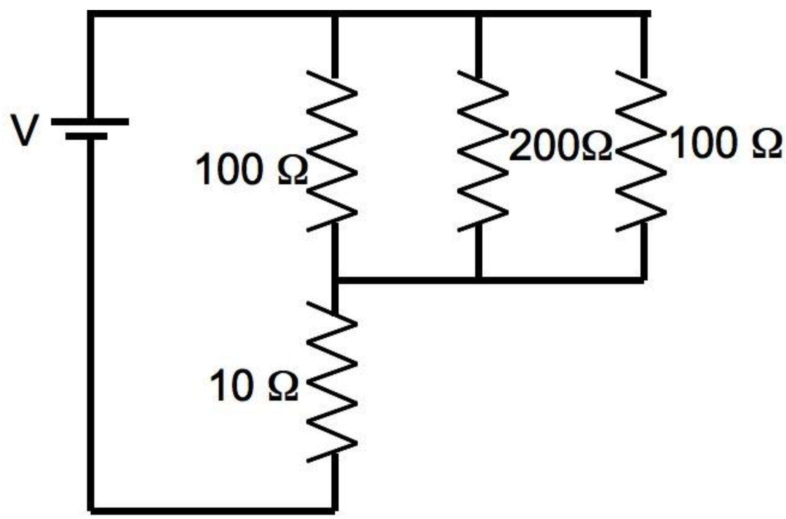
The circuit shown above has 3 resistors in parallel, which *together* are in series with another resistor. Extend your equation for the parallel resistance of two resistors to find the equivalent resistance of three resistors in parallel (SI units). Also provide a small sketch of the simplified circuit.

¿ **2-2**

Now use the formula for the equivalent resistance of resistors in series to predict the total resistance of this circuit (SI units).

¿ 2-3

Now set up the circuit and test your prediction by simply using the DMM as an Ohmmeter. Redo 2-1 and 2-2 until you are sure you are calculating your prediction correctly and/or making the measurement correctly.



¿ 2-4

Power the circuit from the previous problem. Be careful not to use too large of a voltage or the resistors will become very hot. Measure the voltage drop across each of the resistors in parallel. What do you find and why?

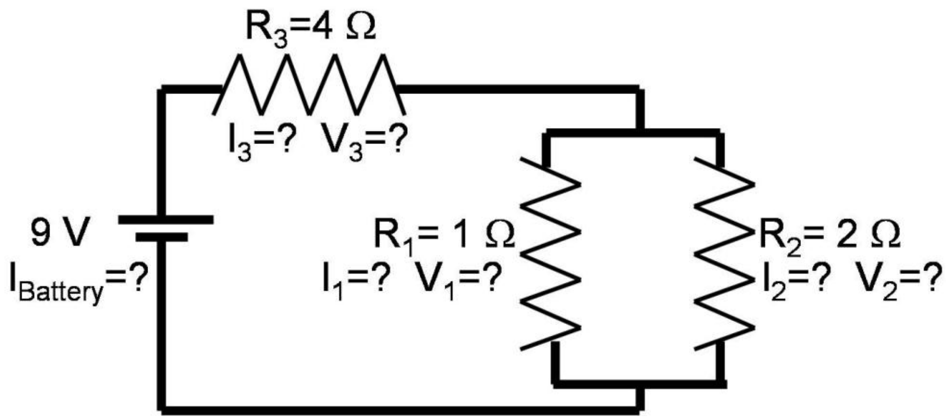
¿ 2-5

Measure the voltage across the 10 [Ω] resistor. Does this value make sense, i.e., does it equal the total applied voltage minus the voltage across the parallel components?

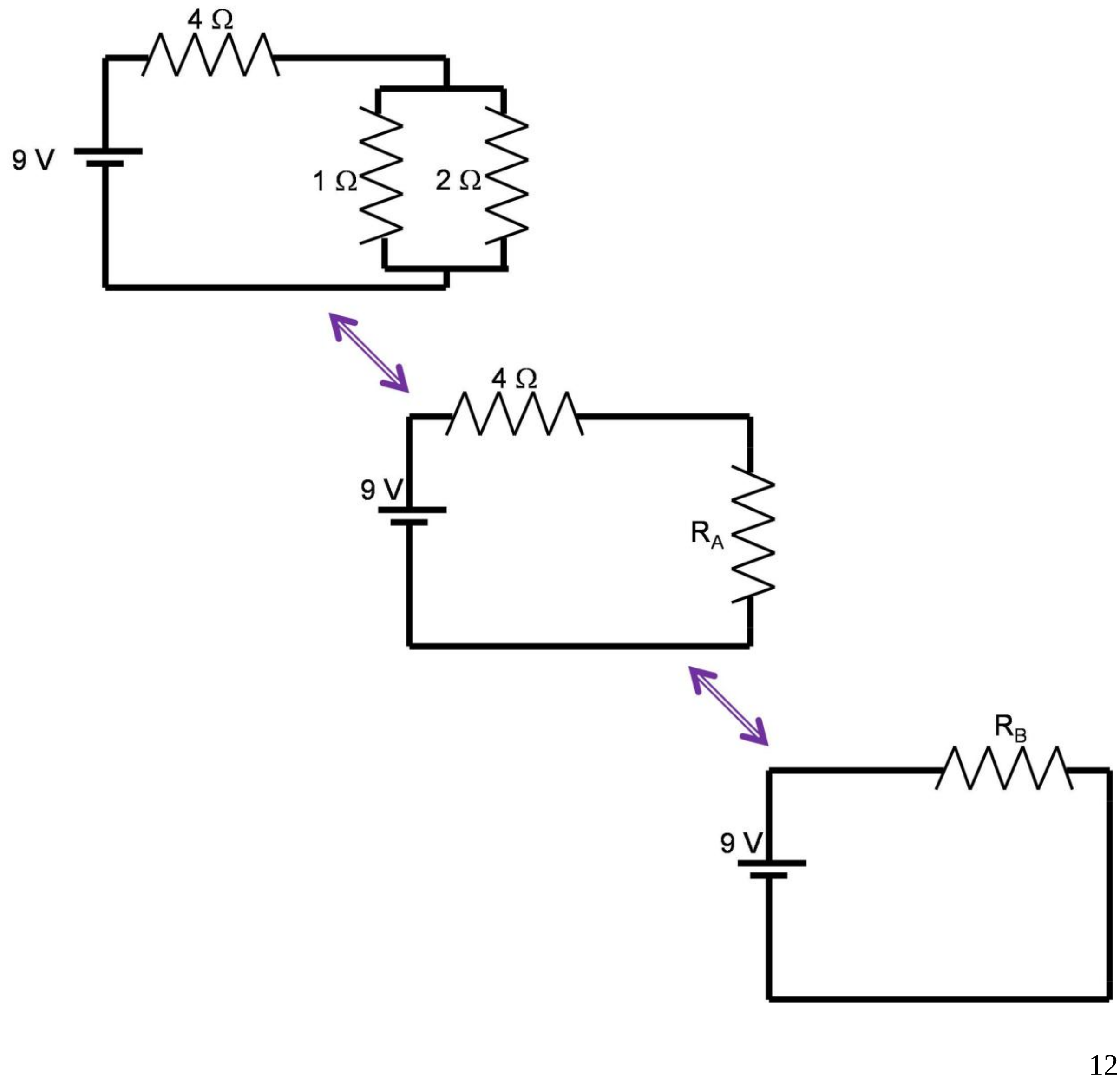
¿ 2-6

Measure the total circuit current. How must the currents in each of the resistors above compare to this. Measure each of the currents in the resistors and check that this is so. ***Don't cut corners here or you will not do well on the lab practical!***

As more components are added to the circuit, the problem solving becomes more complex. Here you must solve for the total current $I_{Battery}$, the total resistance R_{total} as well as the voltages across and currents through each of the components:



First find the total equivalent resistance. This must be done in steps:



- First collapse the first two parallel components: $R_A = \dfrac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2}} = \dfrac{2}{3}\ [\Omega]$. Then collapse the two series components: $R_{\mathrm{B}} = R_3 + R_A = \dfrac{14}{3}\ [\Omega]$. Since this is actually the total resistance of the circuit (assuming an ideal battery which has zero internal resistance), you may use Ohm's law to find the total current: $I_{\text{Battery}} = \dfrac{V_{\text{Battery}}}{R_{\mathrm{B}}} = \dfrac{27}{14}\ [\mathrm{A}]$.

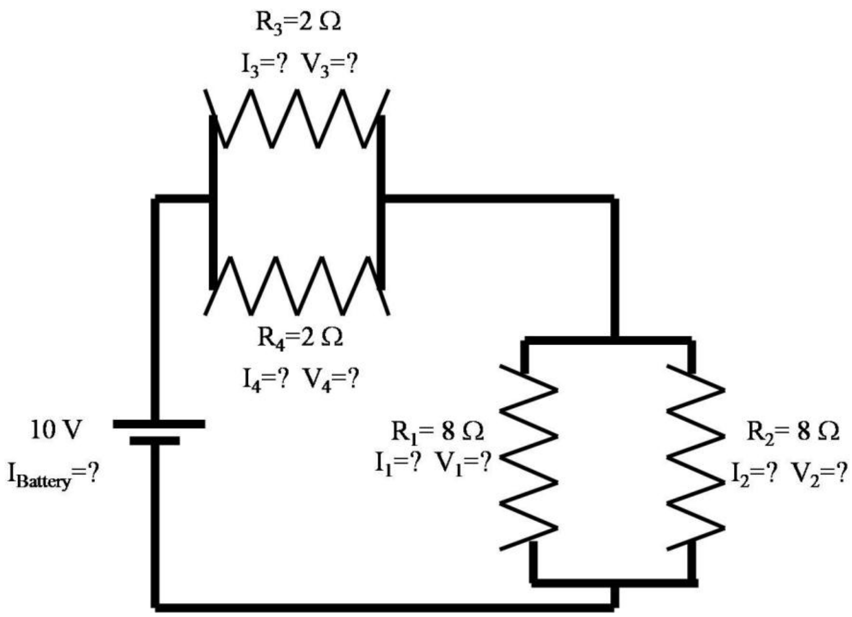
- Since charge cannot pile up anywhere in a circuit, this is also the same current as in R_3: $I_3 = \dfrac{27}{14}\ [\mathrm{A}]$. You can now find the voltage across R_3: $V_3 = R_3 I_3 = \dfrac{54}{7}\ [\mathrm{V}]$.

- Now note that R_1 and R_2 are in parallel so that V_1=V_2 (remember conservation of energy in circuit loops). Subtract V_3 from the total voltage to find the voltage across these parallel resistors: $V_1 = V_2 = 9 - \dfrac{54}{7} = \dfrac{9}{7}\ [\mathrm{V}]$. Now you can easily find the current in each component: $I_1 = \dfrac{V_1}{R_1} = \dfrac{9}{7}\ [\mathrm{A}]$ and $I_2 = \dfrac{V_2}{R_2} = \dfrac{9}{14}\ [\mathrm{A}]$. Check your parallel currents as they must add up to the total $I_1 + I_2 = \dfrac{9}{7} + \dfrac{9}{14} = \dfrac{27}{14}\ [\mathrm{A}]$, which is the total current coming into the parallel components. Also note that since R_2 has twice the resistance of R_1, only half as much current flows through that resistor.

The logic is beautiful, but it takes a good amount of practice to learn how to "work inward then back outward" on these kinds of problems.

¿ 2-7

The following compound circuit shows a 10 [V] battery discharging through two parallel 2 [ohm] resistors and two 8 [ohm] resistors in parallel. The two parallel pairs of resistors are themselves in series. You need to find all the unknown component voltages and currents as well as the total circuit resistance and current. You may assume the battery is ideal (has no internal resistance). The answers are given so that you can check your work. Hint: treat each parallel set of resistors as a single equivalent resistor.

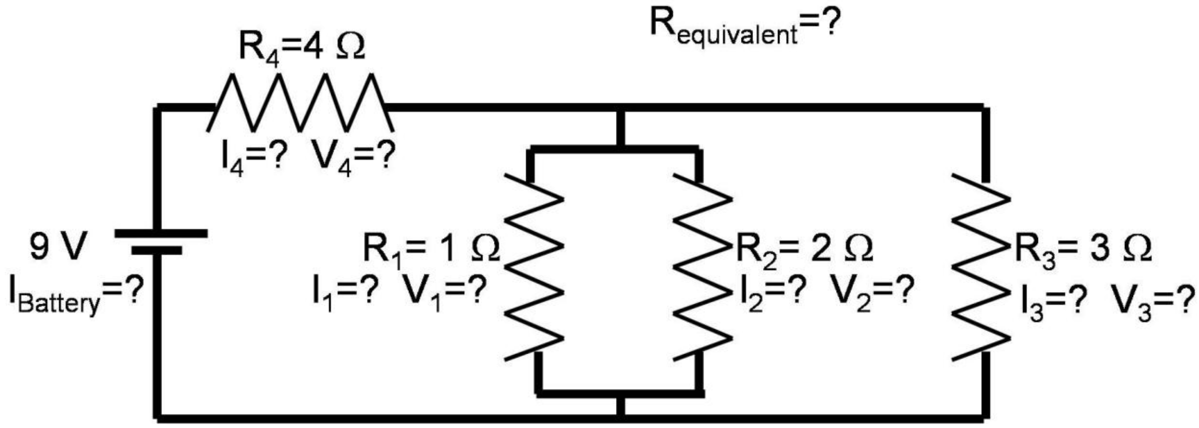


R_{total} = 5 ohms
$I_{battery}$ = 2 amps

$V_1 = V_2$ = 8 volts
$I_1 = I_2$ = 1 amp

$V_3 = V_4$ = 2 volts
$I_3 = I_4$ = 1 amp

Here is an example where you must solve for total current ($I_{Battery}$) total resistance ($R_{equivalent}$) as well as the voltages and currents in each of the components:



First find the total equivalent resistance. This must be done in steps. First collapse the first two parallel components: $R_{12} = \dfrac{1}{\dfrac{1}{R_1}+\dfrac{1}{R_2}} = \dfrac{2}{3}\Omega$. Then collapse this with R_3: $R_{123} = \dfrac{1}{\dfrac{1}{R_{12}}+\dfrac{1}{R_3}} = \dfrac{6}{11}\Omega$.

Finally collapse these with the remaining R_4: $R_{\text{effective}} = R_4 + R_{123} = \dfrac{50}{11}\Omega$.

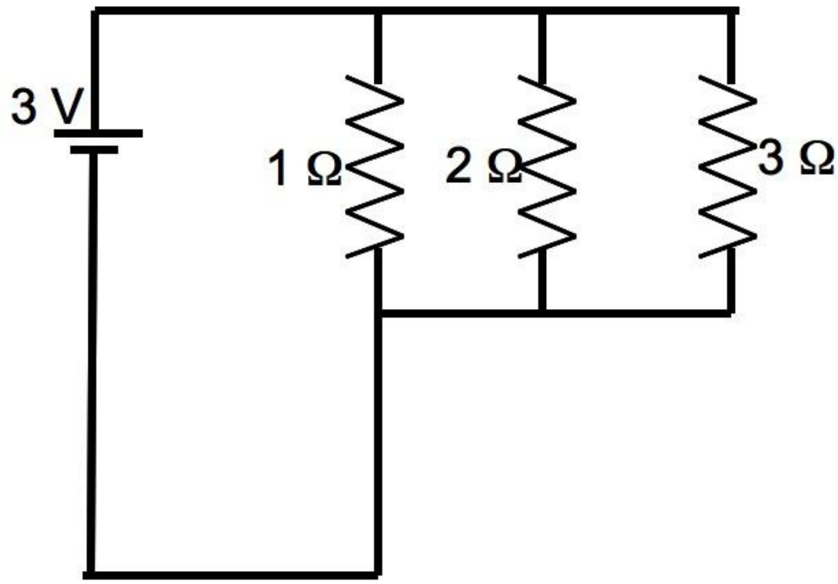
With the total resistance, you may use Ohm's law to find the total current: $I_{\text{Battery}} = \dfrac{V_{\text{Battery}}}{R_{\text{effective}}} = \dfrac{99}{50}\text{Amps}$. This is also the same current as in R_4: $I_4 = \dfrac{99}{50}\text{Amps}$. You can now find the voltage across R_4: $V_4 = R_4 I_4 = \dfrac{198}{25}$ Volts.

Now note that R_1, R_2 and R_3 are in parallel so that $V_1=V_2=V_3$ (conservation of energy in loops). Subtract V_4 from the total voltage to find the voltage across each parallel component: $V_1 = V_2 = V_3 = 9 - \dfrac{198}{25} = \dfrac{27}{25}$ Volts.

Now you can easily find the current in each component: $I_1 = \dfrac{V_1}{R_1} = \dfrac{27}{25}\text{Amps}$, $I_2 = \dfrac{V_2}{R_2} = \dfrac{27}{50}\text{Amps}$, and $I_3 = \dfrac{V_3}{R_3} = \dfrac{27}{75}\text{Amps}$.

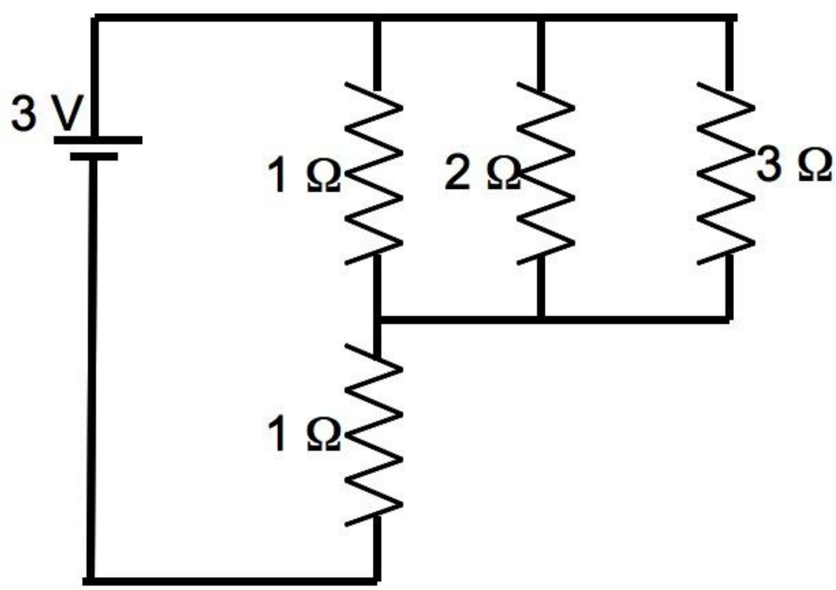
¿ 2-8

Calculate the <u>total</u> circuit resistance and <u>total</u> circuit current. Then calculate the current through the 3 ohm resistor.



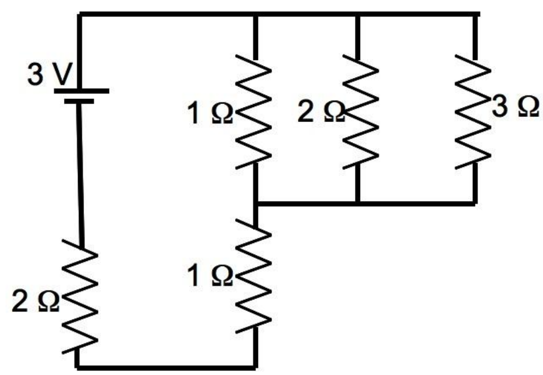
¿ 2-9

Calculate the <u>total</u> circuit resistance and <u>total</u> circuit current. Then calculate the current through the 3 ohm resistor.



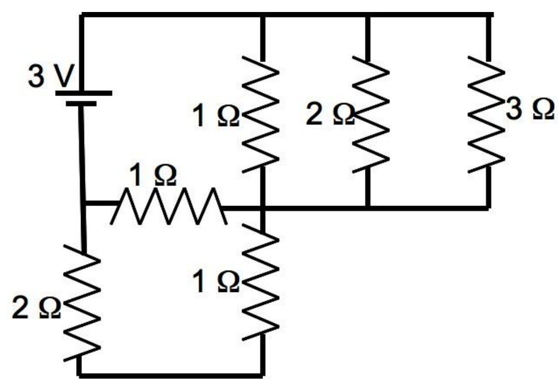
¿ **2-10**

Calculate the <u>total</u> circuit resistance and <u>total</u> circuit current. Then calculate the current through the 3 ohm resistor.



¿ **2-11**

Calculate the <u>total</u> circuit resistance and <u>total</u> circuit current. Then calculate the current through the 3 ohm resistor.

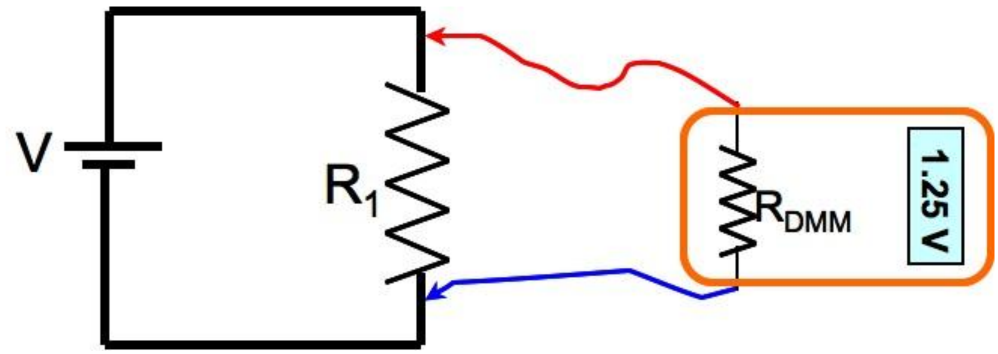


¿ **2-12**

Would you have predicted that the total current for the last two circuits would be so different? Explain why the addition of the single 1 [Ω] resistor in the fourth circuit increases the total current by almost 300%. Your answer and explanation:

Section 3: the internal resistance of a DMM

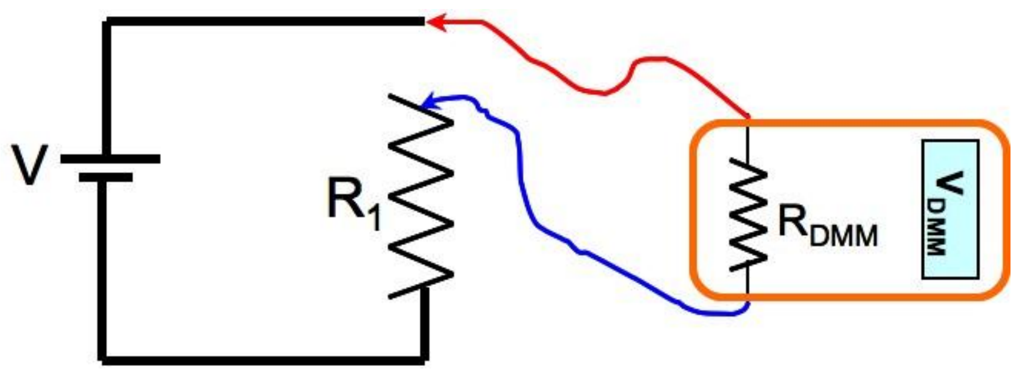
Your DMM has a very large internal resistance. Sometimes it is important to know this value because if you try to measure circuits with comparably large resistances, the DMM begins to carry an appreciable part of the circuit current throwing off measurements. For example, in the following picture a DMM is used to measure the voltage across a resistor.



Consider what happens if the internal resistance of the DMM is near to that of R_1. It behaves like any resistor by letting current flow through it which we don't want because the DMM is then *part of the circuit*. Since DMM actually measures voltage by determining the current flowing through it, a false reading is obtained.

We can find the internal resistance of the DMM by deriving a useful formula relating R_{DMM} to other variables, and then measuring the other variables experimentally.

Theoretically examine the circuit with R_1 placed in series with the DMM. (You won't be asked to set up the circuit and make measurements until a later problem.)



¿ 3-1

Predict the total resistance of this circuit from the two component resistances.

¿ **3-2**

Calculate the total current I in the circuit in terms of V, R_1 and R_{DMM}.

¿ **3-3**

Since the total current is also the current through R_{DMM}, you may also calculate I in terms of R_{DMM} and V_{DMM}.

¿ **3-4**

Equate I in your previous two answers in order to find an equation relating V, R_1, R_{DMM}, and V_{DMM}.

¿ **3-5**

Rearrange your previous answer in order to obtain: $R_{\mathrm{DMM}} = \frac{V_{\mathrm{DMM}}}{\mathrm{V} - V_{\mathrm{DMM}}} R_1$.

¿ **3-6**

With the aid of your derived formula (given in 3-5), use your DMM and the 10 [MΩ] resistor to find the internal resistance of your DMM (10 [kΩ] for the internal resistance of the analog voltmeter if one is provided).

Section 4: authentic assessment

Set up a working circuit that simultaneously uses three resistors *not all in series* and measure the current through each resistor separately using an ammeter. Be sure not to apply too large of a voltage. Sketch your circuit and label the resistances and measured currents of each resistor.

If you are uncomfortable having another student check your work, please ask your TA.

¿ 4-1

Show a student in a different group that you can successfully measure the current through a resistor using an ammeter. Once you are successful, have them sign below. Note: if someone is stuck, please give them advice!

"Yes, I have seen this successfully use make an ammeter measurement. They have not forgotten the major difference between measuring voltage and measuring current with a DMM!"

Student Signature:____

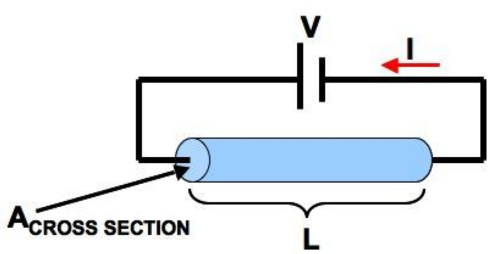
Section 5: open-ended

At each lab station is a long board with Nichrome wire (nickel-chromium) of various thickness. Nichrome wire has a moderately high resistance and is often used in simple heating elements.

Imagine you work for a company that produces resistive wire. You need to determine some basic technical specifications for the resistive wire for use in your sales catalog. Reporting the total resistance is useless since this depends on how thick and long a particular wire is. Instead you should report resistivity ρ with units of Ω m, which is a microscopic description of resistance. This will allow an engineer designing a coffee maker the ability to calculate the size and shape of the Nichrome heating element that they need to order from your company.

The total resistance of a wire increases linearly with the length of the wire, $R \propto L$. However, the total resistance of a wire is inversely proportional to the cross sectional area of a wire, $R \propto \frac{1}{A}$. This is because increasing the thickness of the wire gives the electrons more surface to flow through so that they encounter less "electrical friction".

When someone knows the *proportionalities* of a variable, they can write an *equation* for that variable with an unknown constant: $R = \rho \frac{L}{A}$. Here the resistivity ρ is a constant of proportionality relating the total resistance of a wire to its length and area. Find the resistivity of Nichrome wire.



You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the next page.

¿ 5-1
hypothesizing/planning:

¿ 5-2
observations/data:

¿ 5-3
calculations/conclusion

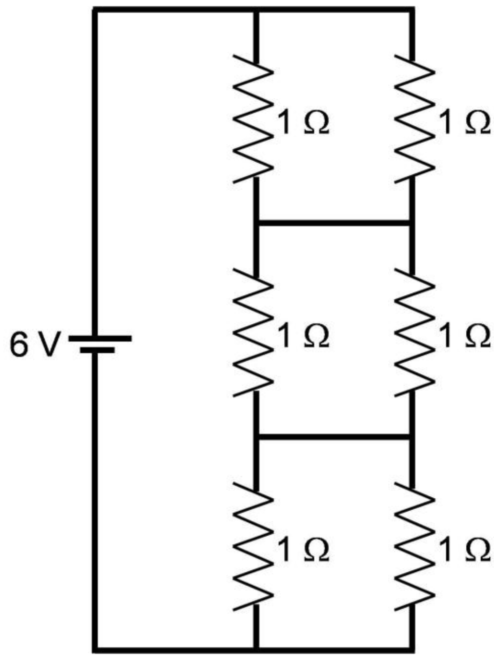
I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: ____**

Week 5 Take-Home Quiz

Score:__________ /5

¿ THQ-1 (5-points)



a) What is the total equivalent resistance of this circuit?

b) What is the total current supplied by the battery?

c) What is the voltage drop across any single resistor?

d) What is the current passing through any single resistor?

e) By only removing *one single wire* how could this circuit be made to have a total equivalent resistance of 2 Ω? Draw your answer on the circuit diagram by placing an 'X' on the wire to be removed.

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Week 6 Pre-Lab: Oscilloscope

Before actually using the oscilloscope, you need to be able to understand and predict what will appear on the oscilloscope screen. An oscilloscope is a device that measures voltage differences over time. It can be used to study rapidly oscillating voltages. For example, the voltage supplied by a wall outlet oscillates at the incredibly slow rate of 60 Hz. Hertz [Hz] is the SI unit for linear frequency representing the number of oscillations per second. However, the oscilloscope can easily measure an oscillation of 1[MHz] or more.

Most DMMs indicate that they can measure an oscillating voltage. However, a DMM can only make average measurements of sinusoidal 60 Hz voltages. In other words, a DMM is only useful for alternating current measurements (AC) on household circuits, not radios or other electronics. *(Remember: $T=1/f$ with SI units [s] and $\omega=2\pi f$ with SI units [1/s].)*

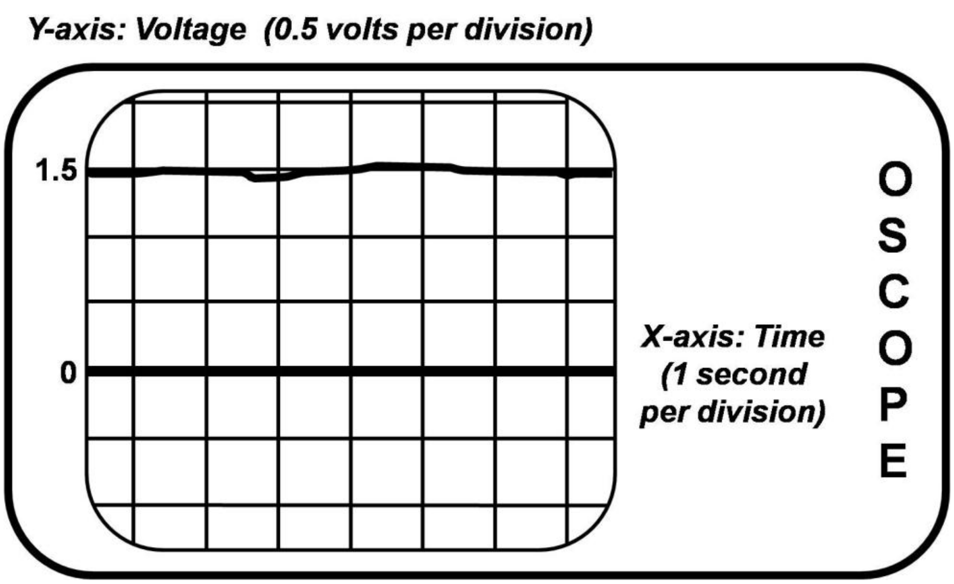
An oscilloscope is needed to examine voltages that change in time. Mathematically, a voltage that oscillates sinusoidally can be written as a time-dependent function (with time measured in seconds [s]):

$$V(t) = 6\sin(2\pi \cdot 60 \cdot t) \text{ [volts]},$$

where f=60 [Hz], $\omega = 2\pi \cdot 60$ [1/s], and $V_{amplitude}$=6 [volts].

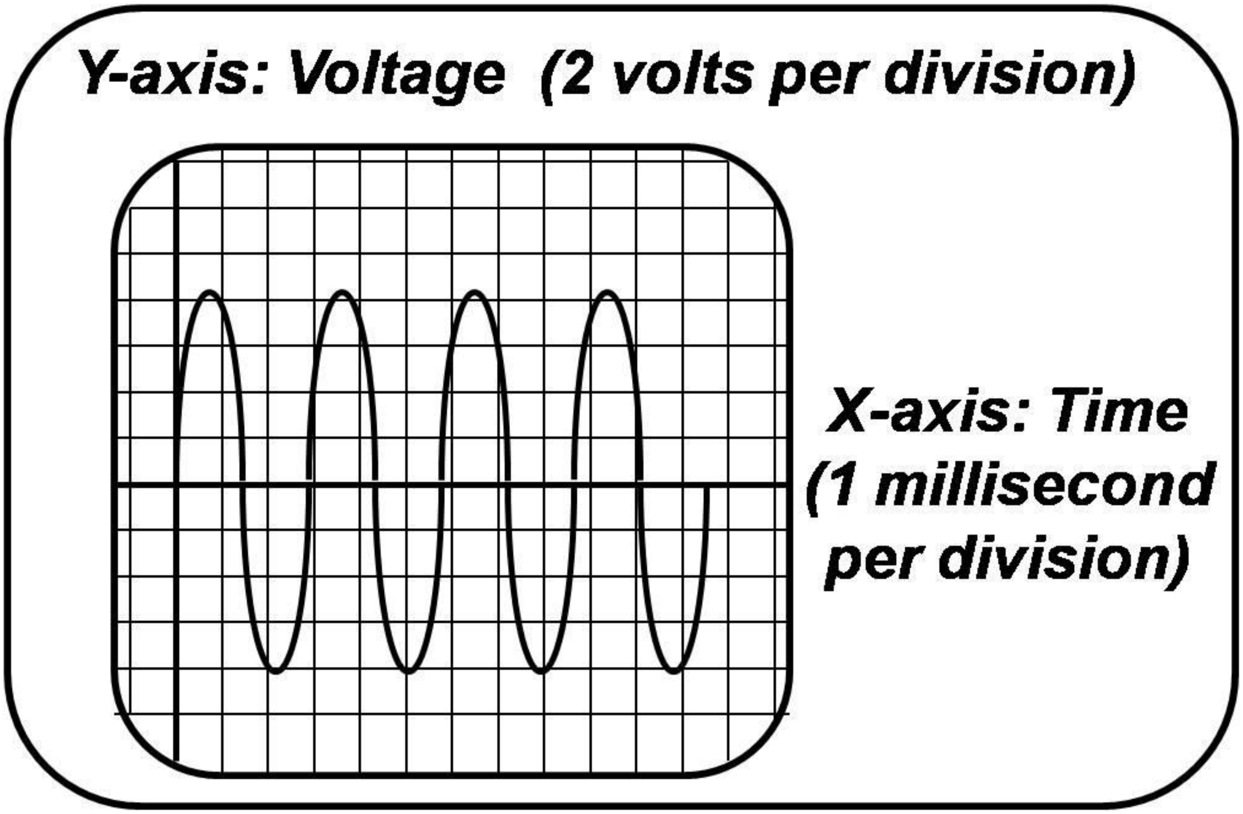
If you are given the oscillating function, $V(t) = 8.21\sin(2250 \cdot t)$ [volts], you should be able to find the various components: $V_{amplitude}$=8.21 [volts], ω=2250 [1/s], $f=\dfrac{\omega}{2\pi} = 358$ [Hz], and T = 1/f = 0.0028 [s].

Imagine you have a 1.5 [V] battery and you put its voltage on the oscilloscope screen. You will see a constant 1.5 [V] on the oscilloscope screen:



A division is one small square on the oscilloscope screen.

Given the sinusoidally oscillating voltage $V_1(t) = 8.21\sin(225 \cdot t)$, this will appear on the oscilloscope screen as.



Note that the amplitude is 8.21 [V] so that the voltage on the oscilloscope screen is seen to reach slightly higher (and lower) than 4 divisions in the y-direction. This is because the oscilloscope is set to 2 volts per division.

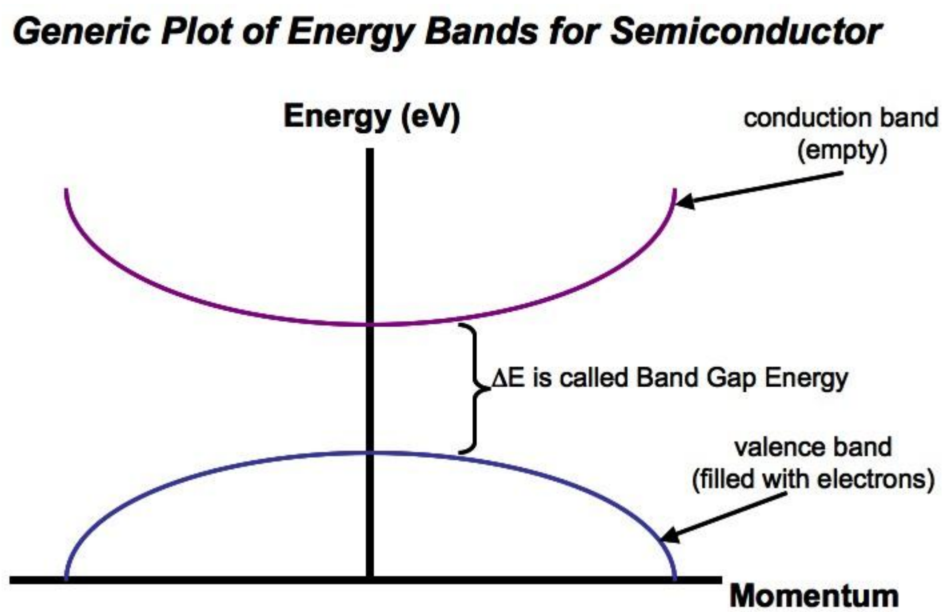
Note that the period is 0.0028 [s] or equivalently 2.8 [ms]. Thus on the screen you see one full wave appearing about every 3 divisions in the x-direction. This is because the oscilloscope is set to 1 millisecond per division.

Week 6 Lab: Oscilloscope

Students Absolutely Must Learn…

- How to relate the mathematics of the sine function to the appearance on the oscilloscope screen of a sinusoidally oscillating voltage.
- The basic concept of how a semiconducting component works, especially relating to its band gap energy (or turn-on voltage).
- How to use an oscilloscope to measure voltage.
- How to set up middle ground and bottom ground simultaneous voltage measurements.

Section 1: semiconductors and quantum mechanics



The above graph shows the 'energy bands' for a generic semiconductor, which must be calculated using quantum mechanics. This graph shows a plot of possible 'energy states' for electrons inside semiconducting material (such as one would find in a computer chip). Though an in-depth discussion of this advanced topic cannot be given here, the most essential points can be provided. The lower energy band of a semiconductor is completely full of electrons. It is out of room so to speak. Electrons in this low energy band cannot accept extra energy unless it is sufficiently large enough to move the electron into the next energy band called a conduction band. Thus a very cold semiconductor cannot conduct electricity because the electrons are stuck in the 'valence band'. But if enough voltage is applied to a semiconductor, the electrons can be given enough energy to escape the valence band and move into the conduction band.

And so you may now guess at how semiconductors provide us a way to create 'digital' electronics, that is, electronics that is either 'on' or 'off', '1' or '0'. With semiconductors, we either

provide enough voltage to allow them to conduct electricity ('on' or '1') or we don't apply a voltage and the semiconductor cannot conduct electricity ('off' or '0').

The most important property of a semiconductor is the minimum distance between the valence and the conduction band because this represents the amount of energy needed to turn on the semiconductor and enable to conduct electricity. This is called the *band gap energy*.

¿ 1-1

If the temperature is low so that each electron in the valence band of the semiconductor has an average kinetic energy much less than the band gap energy, explain whether the semiconductor acts as a conductor or insulator.

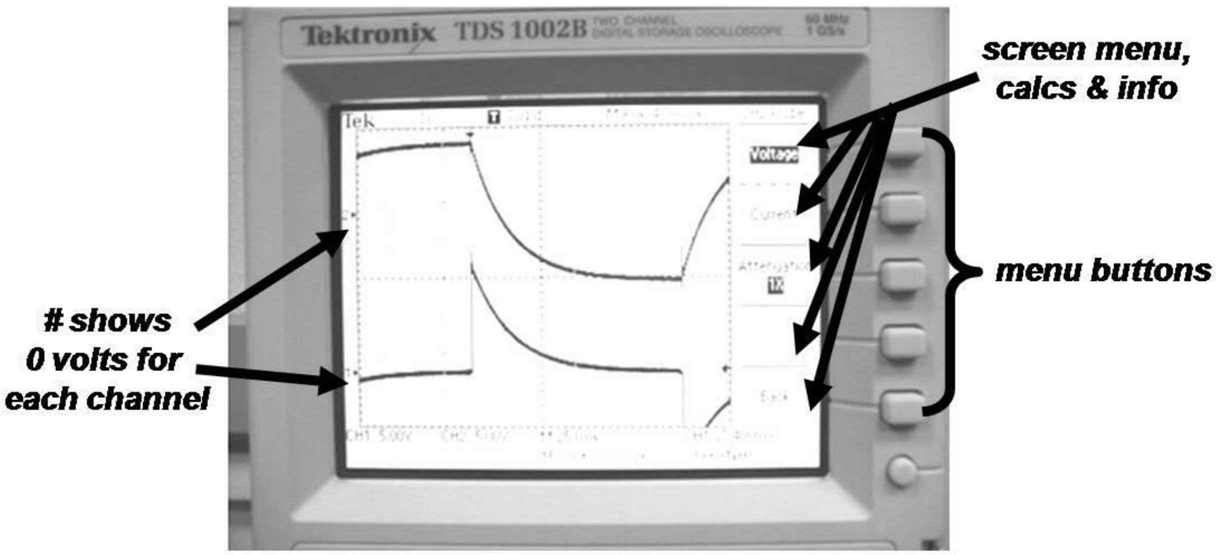
¿ 1-2

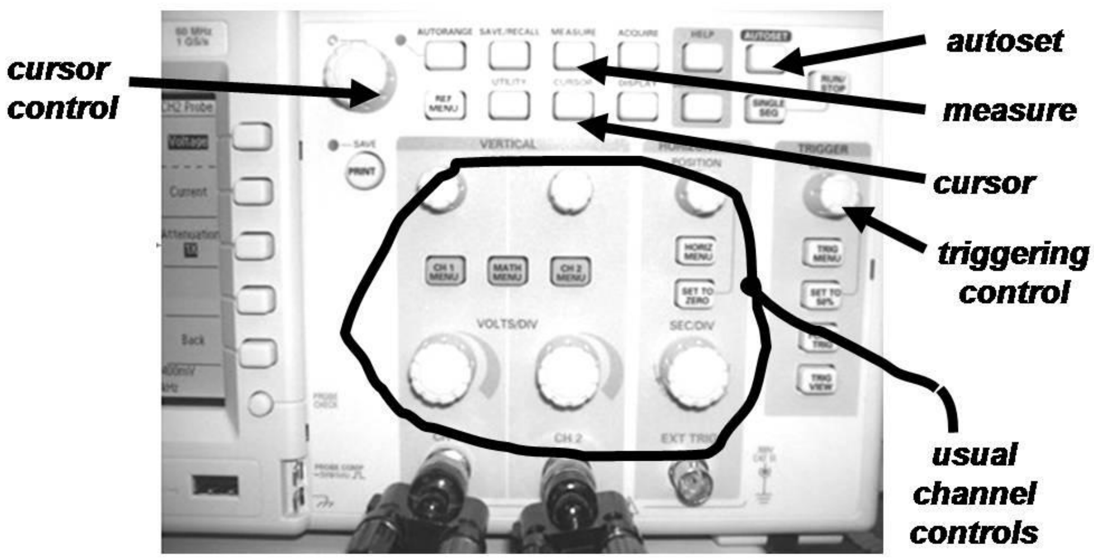
Imagine that an external voltage source is applied across the semiconductor so that each valence electron has more kinetic energy. Approximately what must the applied external voltage be in order for the semiconductor to transition from an insulator to a conductor? (*Hint: energy equals charge times electric potential.*)

Diodes are layered semiconductors and in a simple circuit act as one-way components. Light emitting diodes (LEDs) have a myriad of practical uses. The photons emitted by an LED each have energy roughly equal to the band gap energy of the semiconductor. Laser diodes are conceptually similar to LEDs and have led directly to the “digitized age of music”. More and more electrical engineering programs requiring their majors to gain a firm understanding of quantum mechanics. **(Not a question.)**

Section 2: time dependent voltage on the oscilloscope

The following picture shows the digital oscilloscope and labels its most common features.



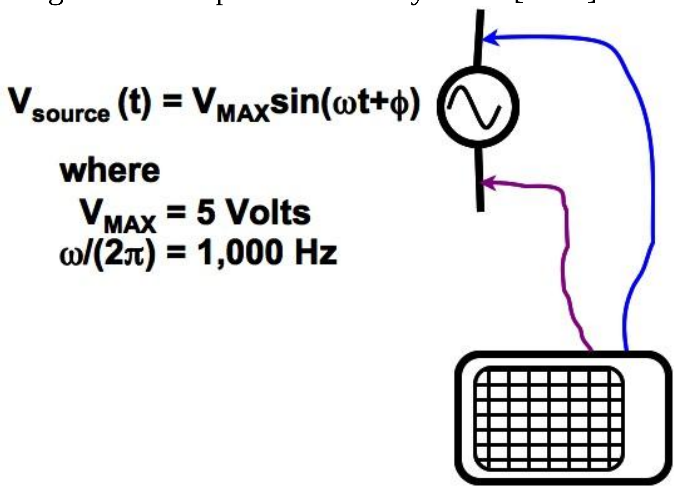


You now need to practice using the digital oscilloscope so that you are prepared to make measurements with it. Keep in mind that the oscilloscope is simply a tool that allows you to analyze the details of a rapidly changing voltage. With that in mind, you will now practice the more common measurements that are made as well as their uses. Your TA will most likely have demonstrated how to use it at the beginning of lab, but each student will forget different features at the beginning stages so work together and ask lots of questions.

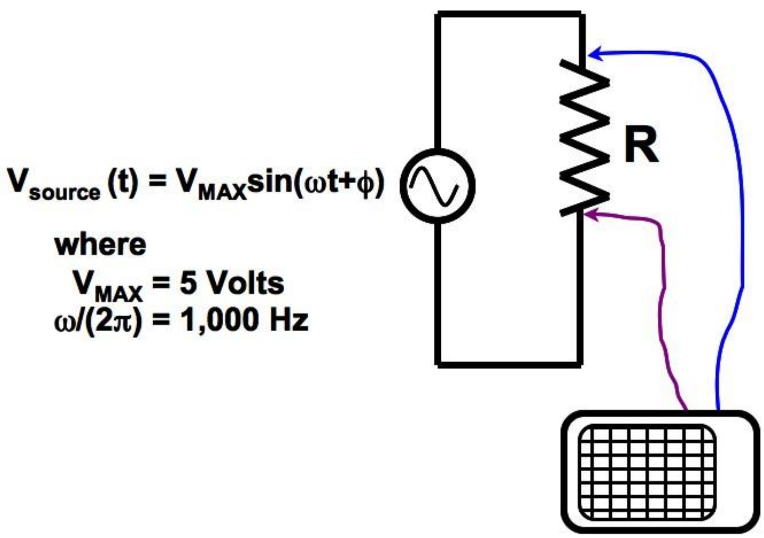
¿ 2-1

Hook the two output leads of your function generator to the two leads of channel 1 of your oscilloscope. Use the oscilloscope to examine the voltage vs. time graphs of many different sine waves, square waves and saw tooth waves created by the function generator (oscillating voltage supply). Be sure to experiment with all sorts of frequencies, voltage amplitudes and DC offsets. Practice making the voltage functions fit nicely on the oscilloscope screen. Take the time to twiddle every knob and switch. Once you feel comfortable with your understanding of each operational control of the oscilloscope and function generator, write a short statement explaining what each control does. *But don't write a "user's manual"*.

The purpose of this next material is to show you that you should never measure the function generator amplitude until **after** you wire it to your circuit. Use the function generator to create a 5 [volt] sine wave with 1,000 [Hz] frequency. Use the oscilloscope (as shown in the picture below) to set the function generator amplitude correctly at 5.0 [volts].



Use this sinusoidal voltage to power a 100 [Ω] resistor. Use the oscilloscope to measure the voltage drop across the resistor (set up as shown in the picture below).



¿ 2-2

What should the voltage drop across the resistor be *according to conservation of energy*? Be sure your measurement with the oscilloscope indicates this.

Now switch to a 10 [Ω] resistor and examine the voltage drop across it. Theoretically, this smaller resistor should still have the same 5 Volt difference (amplitude) as the 100 [Ω] resistor. However, you should notice the voltage amplitude decrease. This is a result of the *function generator output changing*. The smaller resistor will allow a greater current to flow through the circuit, but the function generator has a maximum current that it is able to produce. Therefore, once the resistance becomes too low, the function generator cannot output the full 5 volts. That is why you must measure your output voltage **after** you wire your function generator to your circuit. Just like a battery, a function generator has an internal resistance (~50 [Ω]).

¿ 2-3

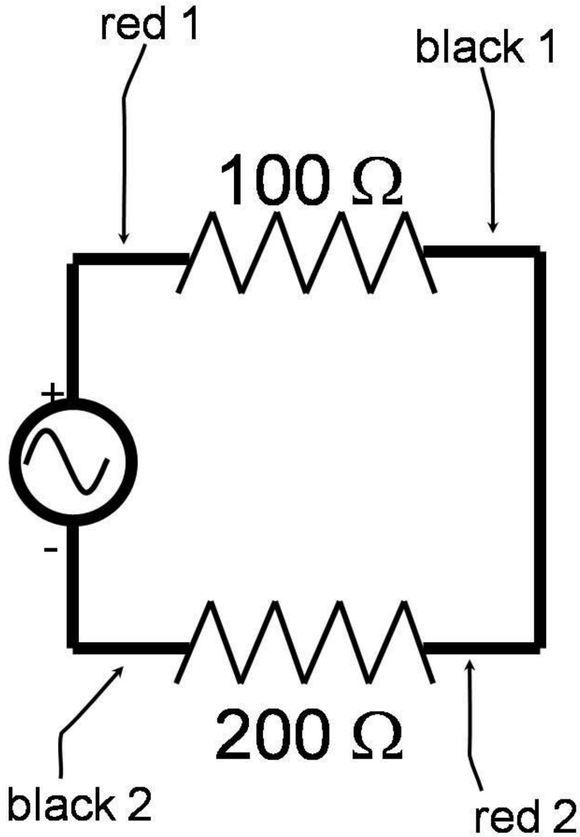
Imagine that you are about to use the function generator to power a circuit. Explain why you should measure the amplitude of the source voltage coming from the function generator <u>after</u> you have hooked up the function generator to your circuit. (Many students get bad data because they forget about this subtle issue.)

¿ 2-4

Use the equation $I_{\text{amplitude}} = \frac{V_{\text{amplitude}}}{\text{R}}$ in with the 10 [Ω] resistor to find the maximum current amplitude $I_{\text{amplitude,max}}$ that the function generator is able to produce.

You may use the oscilloscope to measure the voltages of two circuit components separately using the oscilloscopes two separate channels. The two oscilloscope channels each have a ground (black lead), and both grounds are actually connected inside the oscilloscope so that only one ground needs to be connected to the circuit. A common mistake is for students to try and "sandwich" each component with both channel leads:

! WRONG!

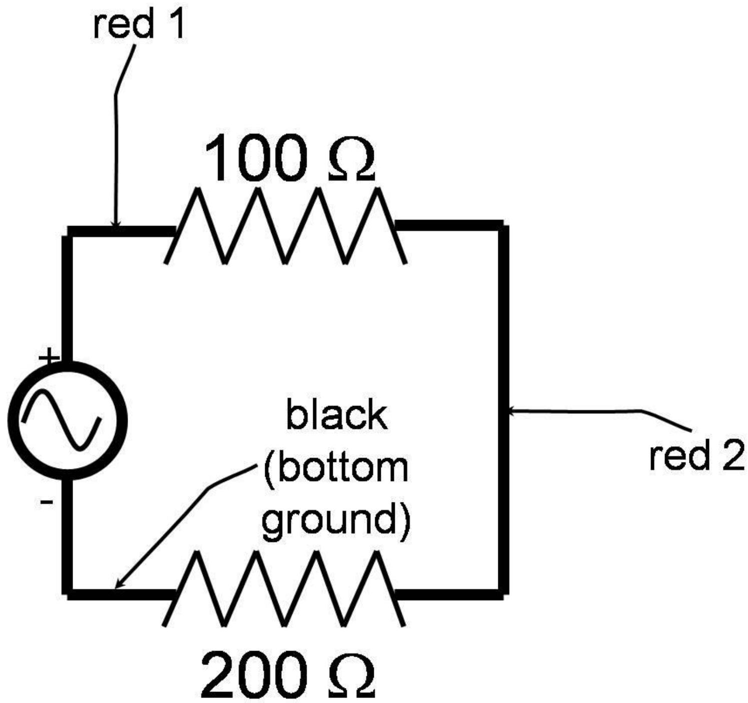


The problem with using both channel grounds is that 1) it is not necessary since they connected internally, and 2) if they end up being connected to different parts of the circuit, they short the circuit out (because they are connected internally). Sometimes students use an external wire to connect both black leads of the oscilloscope channels to remind themselves of this so they don't end up making mistakes (on their lab practicals).

! Never use both channel grounds. Only use one of them, either will do.

Set up the function generator to output a 200 [Hz] sine wave with a 3 [Volt] amplitude through a 100 [Ω] and a 200 [Ω] resistor in series (see figure below).

Use the two oscilloscope channels to measure the voltage across each resistor simultaneously on both channels by setting up a "bottom ground" (set up as shown in the figure below). The voltage between red 1 and ground will tell you the potential difference across both resistors while the voltage between red 2 and ground will tell you the voltage across the 200 [Ω] resistor.



¿ **2-5**

What must you do mathematically to find the voltage across the 100 Ω resistor?

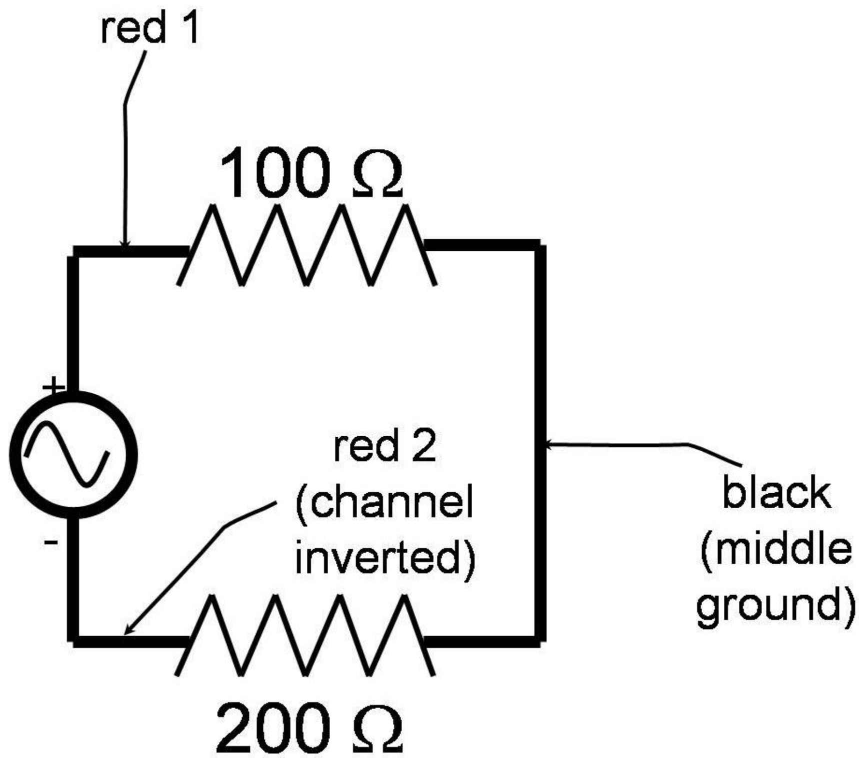
¿ **2-6**

Are the two oscillating voltages across the resistors *in phase* with each other?

¿ **2-7**

Determine the amplitudes of the voltage differences across each resistor and explain why this makes sense.

Now use the oscilloscope to measure the voltage across each resistor simultaneously on both channels by setting up a “middle ground” (set up as shown in the figure below). Note that the middle ground measurement requires that the function generator NOT be grounded (use a 3-to-2 prong plug adapter on the function generator). The voltage between red 1 and ground will tell you the potential difference across the 100 Ω resistor while the voltage between red 2 and ground will tell you the *inverted* voltage across the 200 Ω resistor. The voltage reading is inverted because the order of the positive and negative leads of the second channel are reversed; the same thing would happen with a simple DMM when you switch the leads.



¿ 2-8

What must you do mathematically to find the total voltage drop across both resistors?

¿ 2-9

Are the two oscillating voltages across the resistors *in phase* with each other?

¿ 2-10

Determine the amplitudes of the voltage differences across each resistor and explain why this makes sense.

Using the same middle ground set up as in the last problem, measure the changing voltage across both resistors in "X-Y" mode so that one of the resistor voltages is plotted on the x-axis and the voltage of the other resistor is plotted on the y-axis. You should see an "ellipse edge on" i.e. a diagonal line.

In today's lab we don't have any circuit components that cause phase shifts in their voltages (i.e. capacitors or inductors). These will be used in later labs. Since both resistor voltages are oscillating *in phase* they will both reach zero simultaneously. Thus they will trace a diagonal line that some experimentalists simply consider an ellipse viewed "on-edge".

¿ 2-11

How does the height and width of the "ellipse" in your x-y measurement relate to the voltage amplitudes across each resistor?

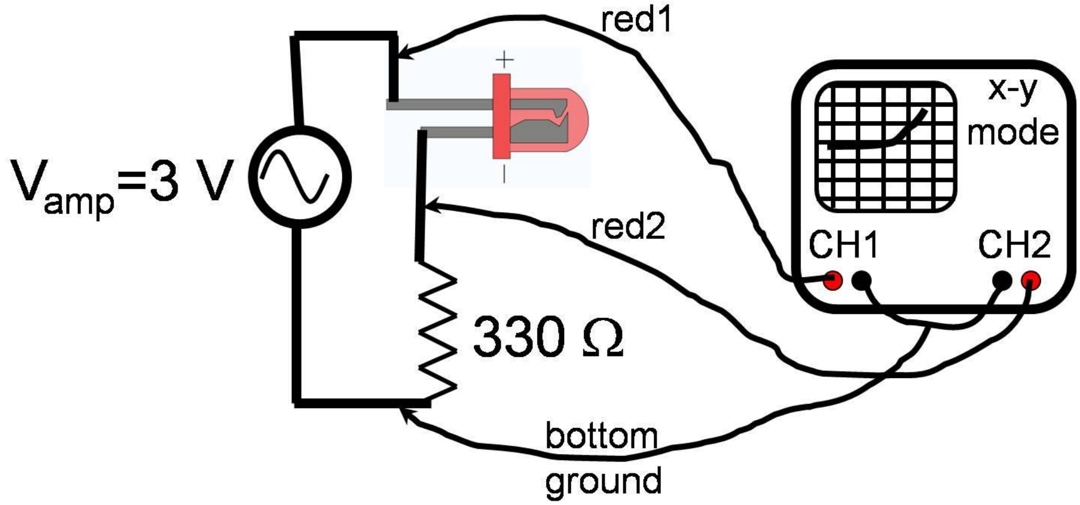
Section 3: non-ohmic diodes

A diode is a one-way circuit component. If a potential difference is applied the wrong way across a diode, it will act as an infinite resistance and not conduct electricity. If a voltage is applied correctly across a diode and above a minimum value, the diode will act with almost zero resistance and allow the current to flow through it. This strange behavior is entirely quantum mechanical and non-Ohmic. This "turn on" effect is related to the band gap energy of the semiconducting materials the diode is made of. (Note that vacuum tubes perform a similar function to diodes and are not quantum mechanical in nature.)

Create the powered diode circuit with a light emitting diode (LED) in series with a resistor. On many diode boards, the diode is already soldered in series with a 330 Ω resistor. Start using a very low source frequency so that you can see the LED blinking as current passes through the LED half the time.

! Do not forget the resistor as it protects the diode from being destroyed by a large current.

Then set up your oscilloscope in the “bottom ground” set up to measure the voltage across the resistor on the y-axis and the applied voltage on the x-axis:



Since the voltage source is oscillating, some of the time it is in the correct direction to "turn on" the diode so that current can flow, and some of the time is in the opposite direction so that no current flows.

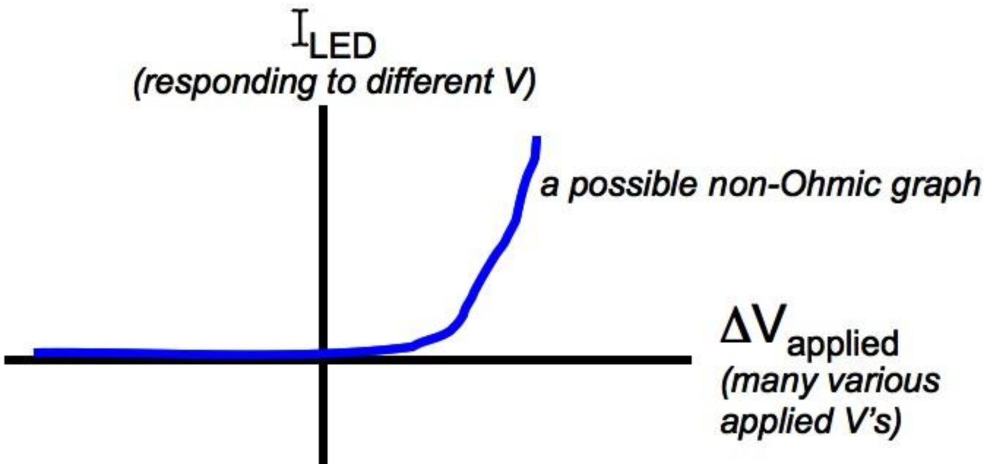
¿ 3-1

When current is not flowing through the circuit, which component has zero voltage drop across it and why?

¿ 3-2

When current flows through the circuit, what is the approximate voltage drop across the light emitting diode? Hint: use the band gap energy.

Experimentally determine if the diode is Ohmic by constructing its current versus applied voltage graph (should look something like example figure below). You may want to increase the source frequency so that the oscilloscope trace makes a solid line. Note that you cannot directly measure the current through the LED with the oscilloscope. Therefore, answer the following questions first in order to learn how to construct the I_{LED} vs. $V_{applied}$ graph.



¿ 3-3

In this circuit, how is the current through the LED related to the current through the resistor?

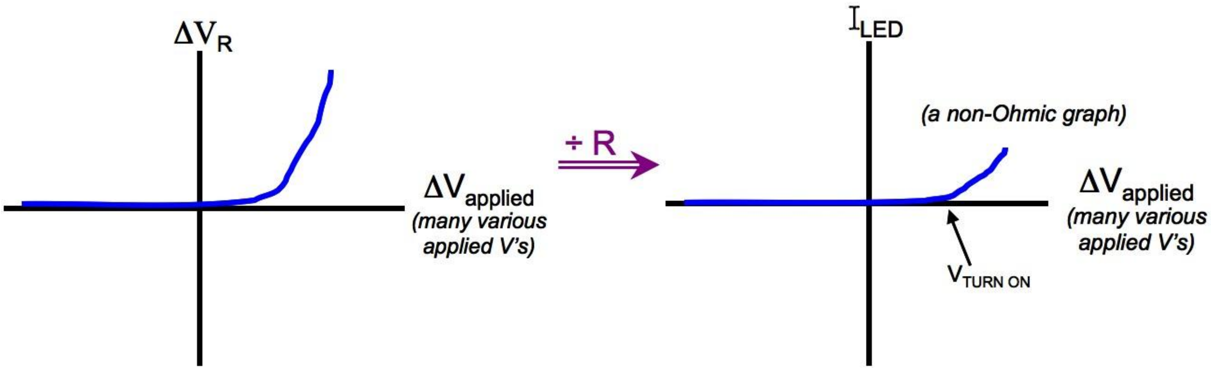
¿ 3-4

Which component of your circuit is known to be ohmic?

¿ 3-5

While the circuit is in operation, if you know the voltage across the resistor and its resistance, what can you find?

Your answers to the previous questions should help you understand that you need to measure the voltage across the resistor in order to find the current through the resistor. Therefore, you need to create the V_R vs $V_{applied}$ graph and turn it into the I_{LED} vs. $V_{applied}$ graph simply by dividing the y-values by the resistors resistance:

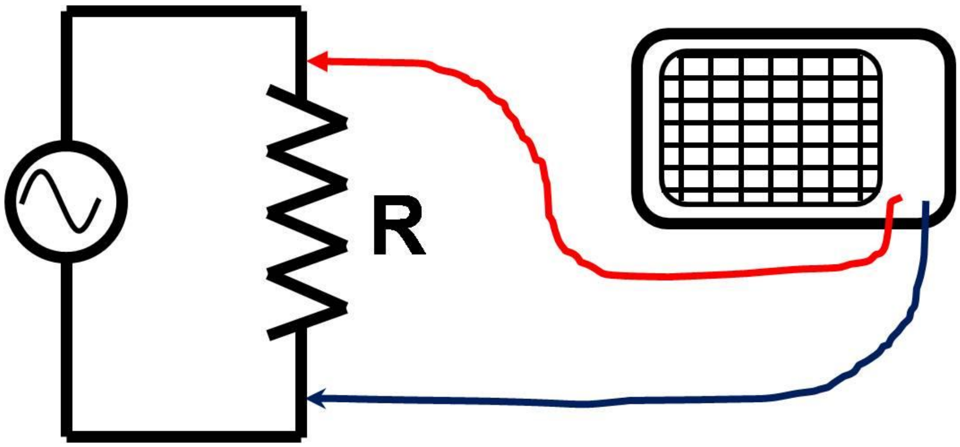


¿ 3-6

Make measurements to obtain the first graph and use it to calculate and create the second graph. Finally, your measurements allow you to experimentally obtain the quantum mechanical property of the material: the turn on voltage so record this value below.
(Note that due to the direction the diode is soldered into the circuit, some students may have 'inverted' readings on the oscilloscope. You may simply "uninvert" this on your graph paper.)

Note: Techincally, the voltage drop across the LED increases as it grows brighter. This is why the slope isn't exactly a constant 1/R.

Section 4: authentic assessment



¿ **4-1**

Quickly set up a working circuit of a resistor powered by a sinusoidal voltage at 100 Hz and measure the *current amplitude* through the resistor. Actually, you can only measure *voltage* with an oscilloscope so you must do this by measuring the voltage drop (amplitude) across the resistor and applying a special amplitude version of Ohm's law, $I_{amplitude} = \frac{V_{amplitude}}{R}$**. Actually, Ohm's law is valid for any point in time, so it must hold at the instant when the current and voltage reach their maximums (amplitudes). Show your results to a student in a different group:**

If you are uncomfortable having another student check your work, please ask your TA.

"Yes, I have seen this student use the voltage measurements of an oscilloscope to obtain the amplitude of the current through a resistor. In other words, they know how to find the voltage amplitude and divide by the resistance."

Student
Signature:____

Section 5: open-ended

Prove that a grain-of-wheat light bulb is non-ohmic because of heating affects by examining the correct graph on the oscilloscope.

You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

¿ 5-1
hypothesizing/planning:

¿ 5-2
observations/data:

¿ 5-3
calculations/conclusion

I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: ____**

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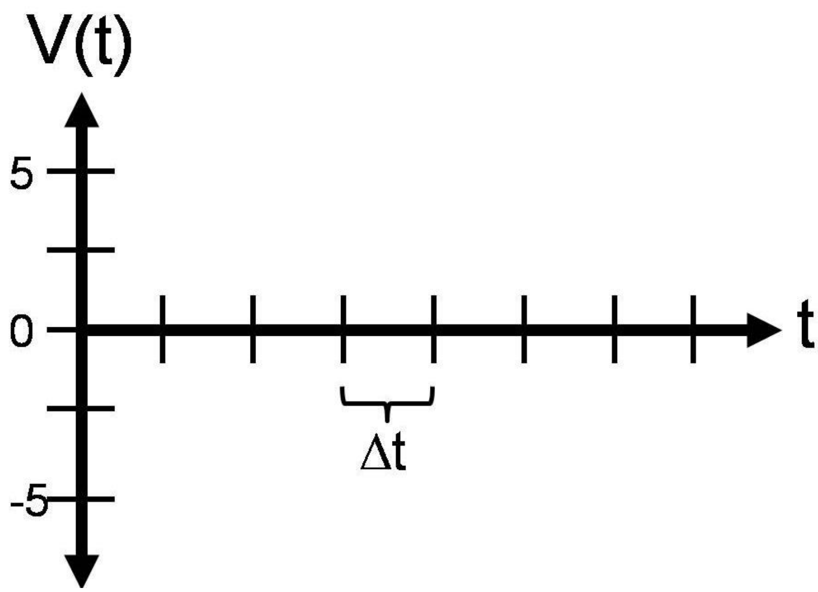
Week 6 Take-Home Quiz

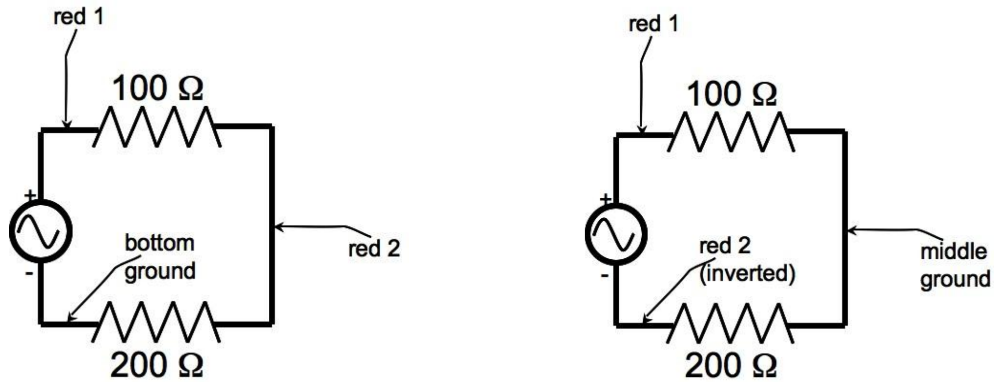
Score:__________ /5

¿ THQ-1 (3-points)

Which would be the best choice for time steps Δt when graphing $V(t) = 8\sin(5{,}000 \cdot t)$ **[volts] with time measured in [s] in order to observe 3-10 oscillations on the graph below?**



¿ **THQ-2 (2-points)**



Which method is better for measuring the separate voltages of two components simultaneously, *middle ground* or *bottom ground*?

Unit 4 Lab Report Instructions

Unit Lab Report [40 points]

Use the following section titles in your report. Images, text or equations plagiarized from the internet are not allowed! Remember to write your report *alone* as collaborating with a lab partner will make you both guilty of plagiarism. **Please label your lab report sections:**

- **Title [0 points]** – A catchy title worth zero points so make it unique and fun.
- **Mini-Report [10 points]:** ***{4-6 paragraphs, ~2 double-spaced pages}***
  Choose **one** of the following sections about which to write your mini-report:
  Week 7 Section 3 or Week 8 Section 3
  Write a "mini-report" for one particular section of the lab manual. Describe what you did succinctly, and then what you found accurately. Then explain what the result means and how it relates to some of the concepts in the previous section. *You must write using sentences & paragraphs; bulleted lists are unacceptable.* ***Please label your mini-repot sections:***
  - **Abstract:** Write 2-3 sentences about the goals of this section. Describe the concepts you were investigating and how the experimentation you performed allowed you to investigate these concepts. Write 2-3 sentences summarizing the procedure. Write 2-3 sentences summarizing the results and what the results mean with regard to the concepts you were investigating. *It is best to write the abstract last*.
  - **Procedure:** Do not provide a lot of specific details, but rather you should summarize the procedure so that a student who took the course a few years ago would understand what you did.
  - **Results:** Provide a description of the data you obtained such as data tables. Restate any measured values, calculated slopes of lines-of-best-fit, etc. Do not *interpret* your results, save any interpretation for the discussion.
  - **Discussion:** Analyze and interpret the results you observed/measured in terms of some of the concepts and equations of this unit. It is all right to sound repetitive with other parts of the report.
- **Open-Ended Discussion [10 points]** – ***{1-2 paragraphs, ~1 page double-spaced}*** Choose **one** of the open-ended experiments from the two weekly activities to write about. Describe your experimental goal and the question you were trying to answer. Explain the ideas you came up with and what you tried. If your attempts were successful, explain your results. If your attempts resulted in failure, explain what went wrong and what you would do differently in the future. *You must write using sentences & paragraphs; bulleted lists are unacceptable.*
- **Graphs [5 points] - {attach to your typed report}** Graphs must be neatly hand-drawn <u>during lab</u> on graph paper. Your graphs must fill the entire page (requires planning ahead), include a descriptive title, labeled axes, numeric tic marks on the axes, and unit labels on the axes. If instructed to calculate the slope of the line-of-best-fit, write it directly on the graph.
  Week 7: 1-4, 1-6, 3-14
  Week 8: 2-4
- **Take-Home Quizzes [2x5 points = 10 points] - {attach after your Graphs}**
- **Selected Worksheet Pages [5 points] - {attach after your Take-Home Quizzes }**
  Your TA will choose which pages you need to hand in.

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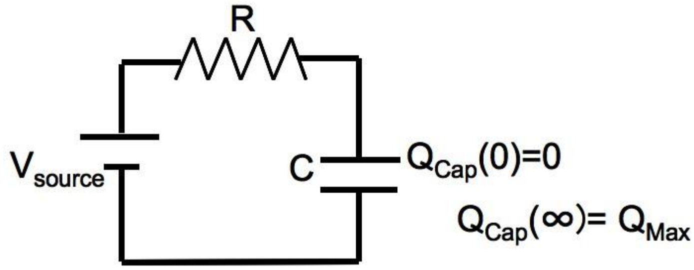
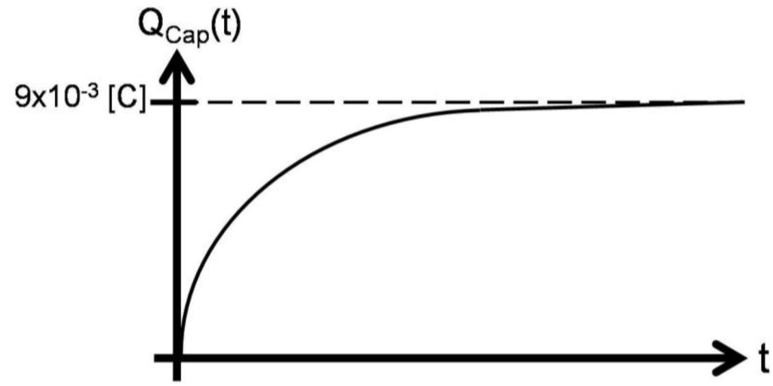
Week 7 Pre-Lab: RC Circuits - DC Source

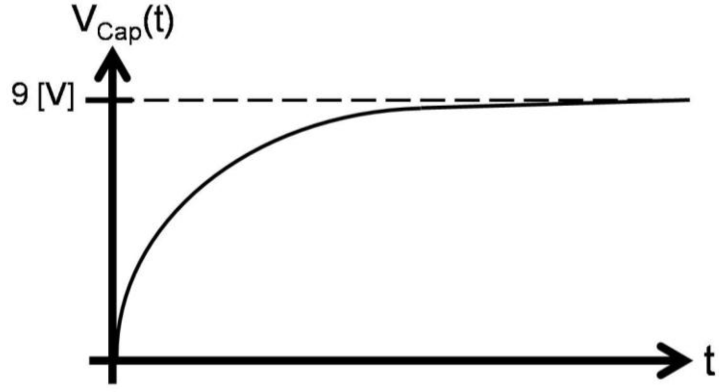
Examine *charging up* the capacitor in an RC circuit. In this circuit, the capacitor begins without any charge on it and is wired in series with a resistor and a constant voltage source. The voltage source begins charging the capacitor until the capacitor is fully charged. The *charging up equation* that describes the time dependence of the charge on the capacitor is $\mathrm{Q_{Cap}}(t) = Q_{\max}\left(1 - e^{-\frac{t}{RC}}\right)$. The final charge on the capacitor, Q_{max} is determined by the internal structure of the capacitor (i.e. its capacitance): $Q_{\max} = C \cdot V_{\mathrm{source}}$.



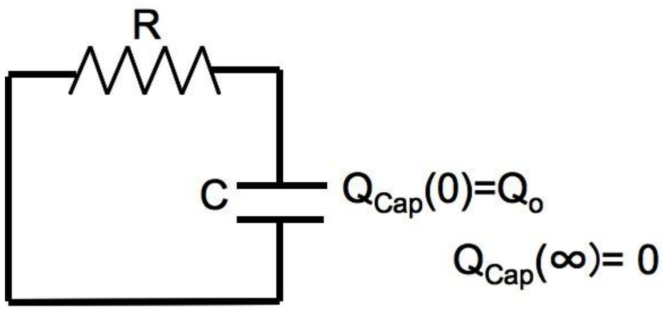
As an example, imagine $\mathrm{V_{source}} = 9$ [V] and $C = 1.0x10^{-3}$ [farad] with the initial charge $\mathrm{Q_{Cap}}(0) = 0$, then the final charge $\mathrm{Q_{Cap}}(\infty)$ on the capacitor can be found using $Q = C \cdot V = 9.0x10^{-3}$ [coul]. A sketch of how the capacitor will charge up is given by

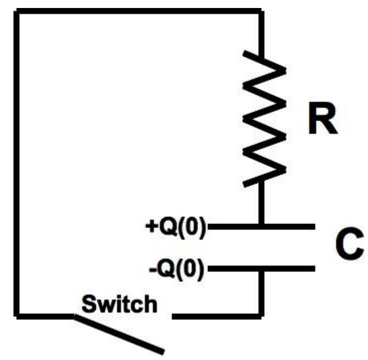


where the time to charge is larger when there is more resistance. Of course you could charge the capacitor without the resistor, and then it will charge very quickly since there will be only a minute resistance in the circuit. The voltage across the capacitor rises similarly:

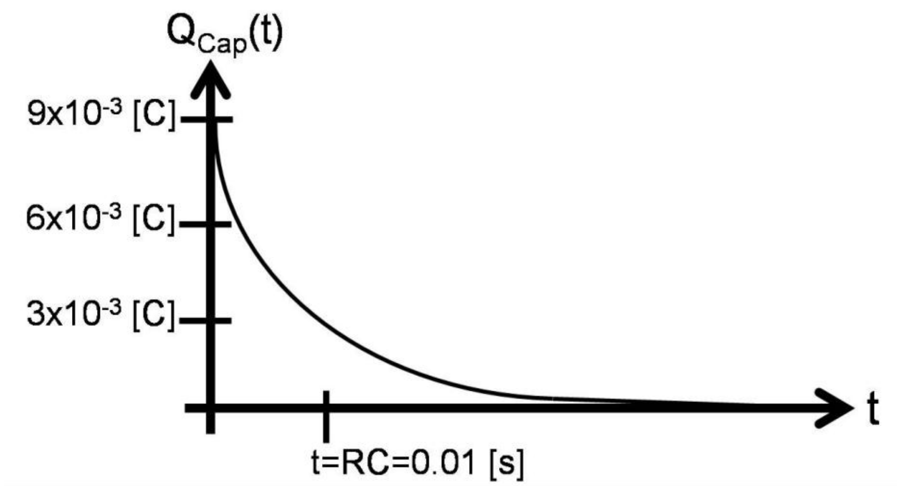


The *discharging* of the capacitor in an RC circuit occurs when the capacitor begins with some initial charge Q_o and is wired in series with a resistor. The capacitor begins discharging through the resistor until no charge remains on the capacitor plates. The *discharging equation* that describes the time dependence of the charge on the capacitor is $Q_{Cap}(t) = Q_o e^{-\frac{t}{RC}}$. It helps to think of an RC circuit with a charged capacitor that has a switch that is about to be closed so that the capacitor can discharge.





If the capacitor begins with $Q_o = 9.0x10^{-3}$ [coul], $C = 1.0x10^{-3}$ [farad] and $R = 10$ [Ω], then $V_o = \frac{Q_o}{C} = 9.0$ [V] and $RC = 1.0x10^{-2}$ [seconds]. Notice that [resistance] times [capacitance] equals [time] since $\frac{t}{RC}$ must be dimensionless. This circuit will discharge as shown:



Note that when t=RC, $\frac{t}{RC} = \frac{RC}{RC} = 1$ so that $Q_{Cap}(RC) = Q_o e^{-1} \approx \frac{1}{3} Q_o$. Thus when t=RC, the capacitor's charge has fallen to approximately 1/3 of its initial value.

Since the resistor is ohmic, we can always find the current moving through it, $I = \frac{V_{Resistor}}{R}$. But in this simple circuit the voltage across the resistor is equal to the voltage across the capacitor which in turn is Q/C. Thus, the magnitude of the current through the resistor is given by $I_{Res}(t) = \frac{Q_o}{RC} e^{-\frac{t}{RC}}$.

Week 7 Lab: RC Circuits - DC Source

Students Absolutely Must Learn…

- The properties of exponential functions.
- How to describe the time dependence of charging and discharging capacitors with exponential functions.
- What differential equations are and how to check their function-solutions.
- Advanced features of oscilloscopes.

Section 1: examining slow RC circuits with a stopwatch

A large capacitance C and large resistance R translate into a slow time constant τ=RC so that you may easily measure the rate of decay with a stopwatch. You are supplied with a 1000 [μF] electrolytic capacitor. Electrolytic capacitors are "one-way" capacitors.

! Be careful to only apply voltage correctly to the electrolytic capacitor or you will damage it (the negative terminal is clearly marked on the capacitor).

You will discharge your capacitor in an RC circuit with approximately 10 [kΩ]. Remember the time dependent equation for the voltage across a discharging capacitor $\mathrm{V}_{\mathrm{Cap}}(t) = V_{\mathrm{o}} e^{-\frac{t}{RC}}$.

¿ 1-1

What time constant τ=RC should you expect with R = 10 [kΩ] and C = 1000 [μF]?

¿ 1-2

Since approximately four time constants 4τ allows the circuit to discharge to about 2% of its initial value (because $\frac{1}{3}\cdot\frac{1}{3}\cdot\frac{1}{3}\cdot\frac{1}{3} = \frac{1}{81} = 0.012$ **or more accurately** $e^{-4} = 0.018$**), how long should you measure the decay of the capacitor's charge in order to make an accurate graph that doesn't take all day to collect data?**

¿ 1-3

Charge an electrolytic capacitor without resistance *in the correct direction* using the 9-Volt battery (this happens quickly since there is very little resistance). Next wire the capacitor to discharge through a ~10 [kΩ] resistor (if the resistance is too small, the capacitor will discharge too rapidly to measure). Collect (voltage, time) data by having the DMM measure voltage across the capacitor while it discharges through the resistor using a stopwatch. You should collect more data at the beginning when there is rapid voltage change. Record your data here:

¿ 1-4

Make a "raw graph" of your data by plotting $V_{cap}(t)$ vs. t.

{On separate graph paper.}

Next you will linearize your data by taking the natural logarithm of your voltages. Since $\mathrm{V}_{\mathrm{Cap}}(t) = V_o e^{-\frac{t}{RC}}$, taking the natural logarithm of the function cancels the exponential:

$$\ln\left(V_o e^{-\frac{t}{RC}}\right) = \ln(V_o) + \ln\left(e^{-\frac{t}{RC}}\right) = -\frac{1}{RC}t + \ln(V_o).$$

The function $y(t) = -\frac{1}{RC}t + \ln(V_o)$ is the equation of a line with a slope of -1/(RC) and y-intercept of $\ln(V_o)$. Thus, if you make the graph of $\ln(\mathrm{V}_{\mathrm{Cap}}(t))$ vs. t on regular (Cartesian) graph paper, you will obtain a line with a slope equal to -1/RC if your data is exponentially related.

¿ 1-5

Linearize your data by taking the natural logarithm of your measured voltages ln(V). Record your data here or in your table from 1-3.

¿ 1-6

Graph your linearized data by taking the natural logarithm of your measured voltages ln(V) and plot these vs. t on regular graph paper. This should give you a line with slope equal to -1/RC.

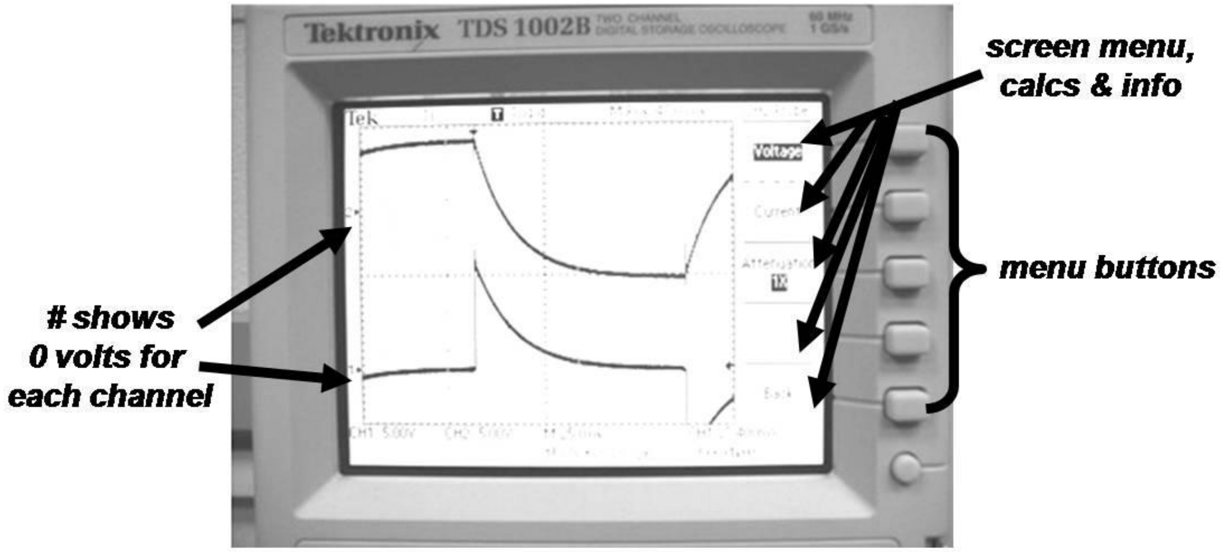
{On separate graph paper, then calculate slope and record here.}

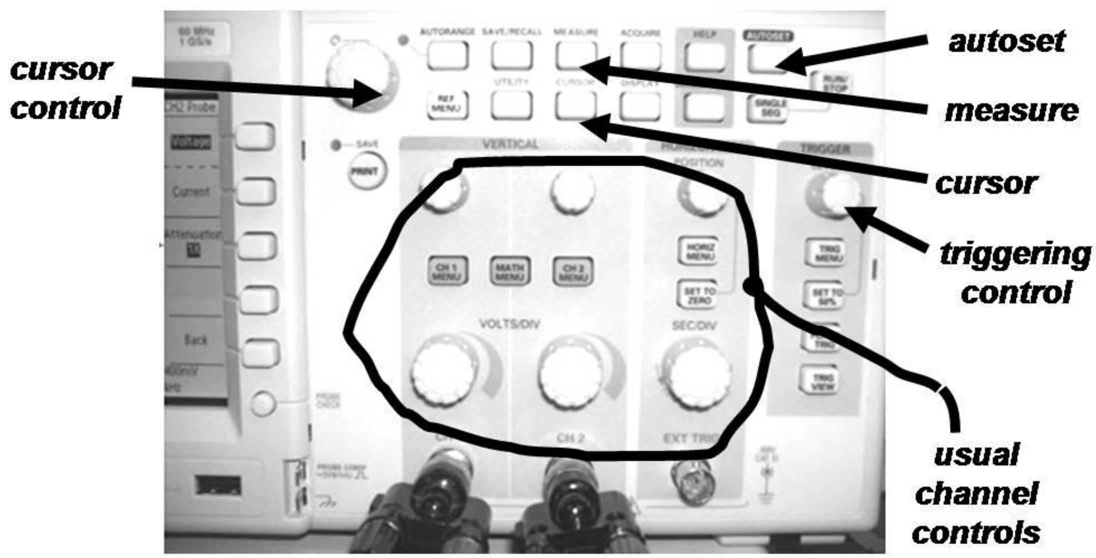
¿ 1-7

Find your experimentally measured value of capacitance C from the slope of your linearized data graph and the value of the resistor's resistance R.

Section 2: more oscilloscope practice

The following picture shows the digital oscilloscope and labels its most common features.





You now need to practice using the digital oscilloscope so that you are prepared to make measurements with it. Keep in mind that the oscilloscope is simply a tool that allows you to analyze the details of a rapidly changing voltage. With that in mind, you will now practice the more common measurements that are made as well as their uses.

¿ 2-1

Hook the output of the function generator directly to one of your oscilloscope channels (and be sure the other channel is shut off). Create a sinusoidal wave with your function generator with a very small voltage (i.e. use a special feature of the function generator and a frequency in the 1-100 [kHz] range. Use the autoset button to quickly get your signal on the screen so you can adjust your function generator DC offset correctly. Be sure that your channel is on "1x probe" and that your trigger is set to the correct source. Do this now and check you work by interacting with students in other groups. {No response necessary.}

¿ 2-2

Use the oscilloscopes measure feature to determine the *average voltage* of your sine wave. Be sure to have about 7-10 full oscillations appear on the oscilloscope screen as the oscilloscope measure feature actually uses the screen for its data (and too few oscillations will create error in the averaging). Record your measurement here.

¿ 2-3

Get the digital oscilloscope to tell you on its screen the wave's period and frequency using the oscilloscope's features. Record your measurements here.

¿ 2-4

Get the digital oscilloscope to tell you on its screen the wave's amplitude. Remember that the 'peak-to-peak' voltage value is twice the amplitude. Record your measurement here.

¿ 2-5

Adjust the amplitude of the wave on the function generator until you see that the wave spends more of its time being negative than positive using the 'DC-offset' feature on the function generator. This will change your average value for the voltage. Use a two cursor measurement *of time* and get the oscilloscope to tell you on its screen how much time the sine wave spends being positive. Then do the same thing to find out how much time the wave spends being negative. Record your measurement here.

¿ 2-6

Now use a two-cursor measurement *in voltage* and get the oscilloscope to tell you on its screen the voltage drop of the wave from its maximum positive value to zero. Record your measurement here.

¿ 2-7

Change your sine wave to a triangle wave of 500,000 [Hz] and use the DC offset so that the minimum of the triangle wave is zero volts. Examine a part of the triangle wave that is decreasing. Use a two cursor measurement to find how long it takes for the triangle wave to decrease from its highest value to one half of that value. Record your measurement here.

Initially, many students become confused about the cause and effect relationship between function generator and the oscilloscope. The function generator is creating the oscillating voltage while the oscilloscope is merely observing it.

¿ 2-8

A student is asked to change the amplitude of a voltage source and begins to push buttons on the oscilloscope. Why is the student's TA disappointed?

¿ 2-9

A student is analyzing a working circuit and is asked after to measure some other feature of the circuit. The student starts turning knobs on the function generator. Explain why the student's TA is yelling in a panicky voice. {Hint: the phrase 'ruined the previous measurements' should appear in your answer.}

Section 3: examining fast RC circuits with an oscilloscope

Most digital electronics make extensive use of capacitors. However, the decay rates are typically much too rapid to measure with a DMM. In this part of the lab you will create an RC circuit using a 0.1 μF capacitor and a 1 kΩ resistor and you will rapidly charge and discharge the capacitor with an oscillating square wave.

¿ **3-1**

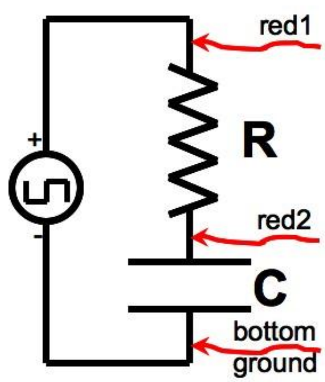
Calculate the time constant τ that an RC circuit using a 0.1 [μF] capacitor and a 1 [kΩ] resistor produce.

¿ **3-2**

You should choose a period of 20τ (or rather a frequency of $1/(20\tau)$ [Hz]) so that there is plenty of time for the capacitor to discharge fully. Calculate this frequency.

¿ **3-3**

Set up the RC circuit shown below powered by a 0 [V] to 3 [V] square wave at the frequency you calculated in the previous question with R=1 [kΩ] and C=0.1 [μF]. Use your function generator to create a square wave with a voltage alternating between V_{MIN} = 0 [V] and V_{MAX} = 3 [V] by first setting the wave to oscillate between +1.5 [V] and -1.5 [V] and then using the DC-offset to shift your signal to have V_{MIN} = 0 volts. The voltage across the capacitor should look like 'shark fins' on your oscilloscope as the capacitor exponentially charges and then exponentially discharges. Do this now and check/discuss with students in other groups to make sure you are getting it correct and understanding fully. Use the same bottom ground setup as shown below:



¿ **3-4**

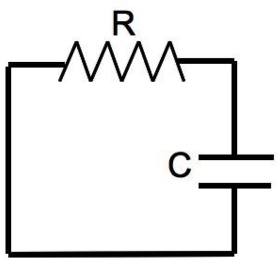
Based on the bottom ground setup shown previously, which oscilloscope channel gives the voltage of the function generator source and which the voltage across the capacitor?

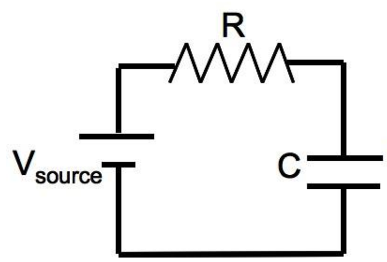
¿ **3-5**

In this setup, is there any special feature of the oscilloscope that will allow you to view the voltage on resistor? {The answer is 'yes', but explain.}

¿ **3-6**

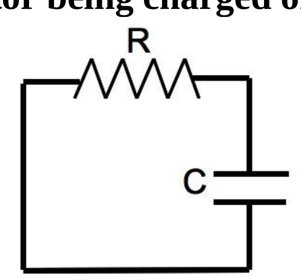
During the time interval that the square wave source voltage is at +3 [V], is the capacitor being charged or discharged? Which circuit below describes the situation?

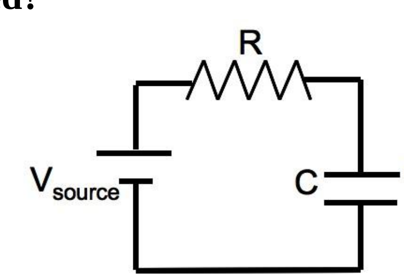




¿ **3-7**

During the time interval that the square wave source voltage is at +0 [V], is the capacitor being charged or discharged?





¿ 3-8

The following is an important reminder that you won't need in today's lab, but is important to remember. Many times you may need to find the current in a circuit. The component you must measure is the resistor because it is the only ohmic device. if you want to determine the current of the circuit and use the oscilloscope to measure the resistor's voltage amplitude, how could you then turn this value into the current amplitude? {Hint: 'ohmic'.}

Observe the voltage across the capacitor and the total circuit voltage simultaneously using a bottom ground configuration. You should see the "shark fin" pattern that is modulated by the alternating square wave source voltage (turning on, then off).

¿ 3-9

Use a double cursor measurement to find the time it takes for your charged capacitor to decrease by half (in SI units so use scientific notation!).

¿ 3-10

When a physical quantity decays exponentially, the time it takes for it to decay to ½ its original value is called the half-life $t_{½}$. Imagine that you need to find the capacitance and are able to measure this half-life time $t_{½}$. Make a formula that gives the capacitance C in terms of $t_{½}$ by solving the *half-life equation* for C: $\frac{1}{2}V_o = V_o e^{-\frac{1}{RC}t_{\text{half}}}$. Show your work.

¿ 3-11

Combine the results of the previous questions and calculate the experimentally determined capacitance C of your capacitor using your half-life measurement in 3-9. This is a way to determine your capacitance with a single measurement (of the half-life).

¿ 3-12

Now use the double cursor method to find the time it takes for your capacitor to discharge from ½ of its initial value to ¼ of its initial value.

The decaying exponential function has the unique property that each consecutive halving of its value occurs in the same amount of time. Thus the half life is an important feature in exponentially decaying systems because no matter when you begin measuring, you know that each half life of time that passes, the value will have decreased by half.

¿ 3-13

Using this knowledge, predict how long it should take for your capacitor to discharge to 1/128 of its initial value (which is approximately 1% of its initial value).

¿ 3-14

A more accurate estimate of C can be made by taking many measurements (similar to that done in 1-3 to 1-7). Use the cursors to collect voltage vs. time data for your decaying capacitor. Then linearize your data, graph it on regular graph paper, and compute to the capacitance C from the slope. Be sure your value is close to the labeled value. Record your data below, linearize your data (record below), make your linearized graph on separate graph paper, find the slope, and calculate C below.

Section 4: authentic assessment

Quickly set up a working circuit that simultaneously uses a capacitor and resistor *in series* powered by a function generator. Use the concept of a half-life and a *single measurement* to determine the capacitance of the capacitor. {Note using t_{half}=0.69*RC is much quicker than finding the slope of a linearized graph with several data points, though much less accurate.} Sketch your circuit and label the resistance of the resistor.

If you are uncomfortable having another student check your work, please ask your TA.

¿ 4-1

Show a student in a different group that you can successfully measure the capacitance of a capacitor with only one measurement. Once you are successful, have them sign below. Note: if someone is stuck, please give them advice!

"Yes, I have seen this student successfully find a capacitor's capacitance using the measurement of the half-life. They are able to *use* this property of exponential decay!"

Student Signature:____

Section 5: open-ended

When capacitors are added in series, they have a combined capacitance determined by one of the two following equations:

$$C_{\text{effective}} = C_1 + C_2 \text{ or } C_{\text{effective}} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}}.$$

Design an experiment to determine which mathematical relationship is correct and which is incorrect.

You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the next page.

¿ **5-1**
hypothesizing/planning:

¿ **5-2**
observations/data:

¿ **5-3**
calculations/conclusion

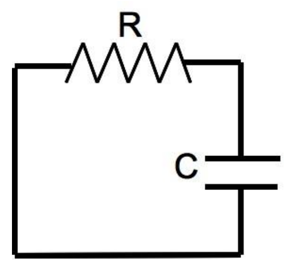
I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: ____**

Week 7 Take-Home Quiz

Score:__________ /5

¿ THQ-1 (5-points)
An initially charged capacitor is discharged through a resistor:



a) Will the capacitor discharge *faster* or *slower* if the resistance is increased (using the same amount of initial charge)?

b) Will the capacitor discharge *faster* or *slower* if the capacitance is increased (using the same amount of initial charge)?

c) As the capacitor discharges, does the magnitude of the current through the resistor *increase* or *decrease*?

d) As the capacitor discharges, what is the magnitude of the current in the space between the plates?

e) As the capacitor discharges through the resistor, energy is being deposited in the resistor as it is heated. Where was this energy stored initially? (Note: your answer must be more explicit than simply stating 'the capacitor'.)

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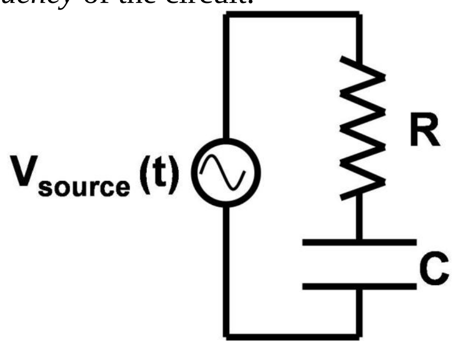
Week 8 Pre-Lab: RC Circuit - AC Source

Last week you studied RC circuits, examining the exponential time dependence of the capacitor voltage as you charged and discharged the capacitor with a constant source voltage. To do this you used a square wave with a DC offset. Now you will examine the behavior of a capacitor when a sinusoidal source voltage is applied: $V_{\text{source}}(t) = V_{\substack{\text{source}\\ \text{amplitude}}} \sin(\omega_D t)$, where ω_D is called the *angular driving frequency* of the circuit.



The capacitor voltage will no longer exhibit exponential time behavior. Instead the capacitor voltage will oscillate sinusoidally with the same frequency as the source driving frequency. The following formulae can be found by solving the appropriate differential equation (not here!). The results of that calculation are provided: the time dependent voltages across each component. Thus, you are not required to be able to derive the solutions to the AC-driven RC circuit, but you must understand and be able to use these results.

Each component of the sinusoidally driven RC circuit has a sinusoidally varying voltage across it, but each peaks at a different time determined by a *phase shift*. Different components reach their maximum voltages at different times than other components.

$$V_{\text{source}}(t) = V_{\substack{\text{source}\\ \text{amplitude}}} \sin(\omega_{\text{D}} t + \phi_{\text{shift}} + \pi)$$

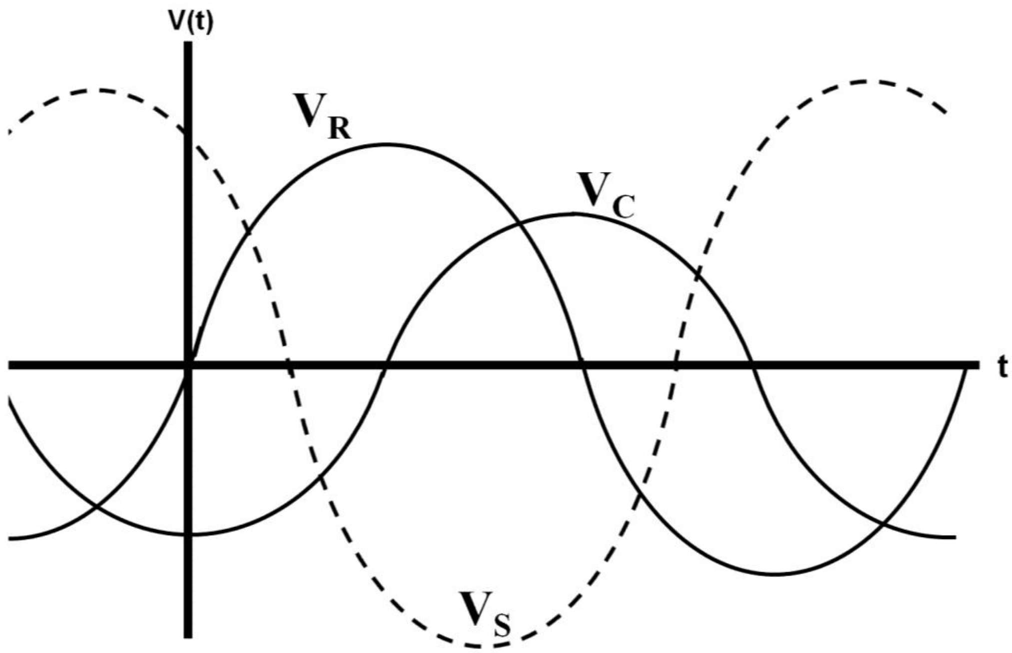
$$V_{\text{Resistor}}(t) = \left(\frac{R}{Z}\right) V_{\substack{\text{source}\\ \text{amplitude}}} \sin(\omega_{\text{D}} t)$$

$$V_{\text{Capacitor}}(t) = \left(\frac{\text{X}_C}{Z}\right) V_{\substack{\text{source}\\ \text{amplitude}}} \sin\left(\omega_{\text{D}} t - \frac{\pi}{2}\right)$$

There are several new parameters to discuss. The reactive capacitance X_C (Greek letter 'chi') is like the resistance of the capacitor and is measured in SI units of [Ω]. But unlike a resistor's resistance, X_C depends on the driving frequency, $\text{X}_C = \dfrac{1}{\omega_{\text{D}} C}$. Note that the capacitor's 'resistance' *decreases* with higher driving frequencies!

Z is the impedance of the whole circuit. Z acts like the "total resistance" of the circuit measured in [Ω], $Z = \sqrt{R^2 + X_C^2}$. At very high driving frequency, X_C becomes very small so that $Z \approx R$.

Notice that the source voltage is now written with a *source phase shift* ϕ_{shift}, the capacitor voltage has a phase shift of $-\pi/2$, and the resistor voltage has *no phase shift*. This can be seen in the following graph.



What this means in practice is that we use the resistor voltage as a reference for all other components in the circuit: i.e. we will measure the phases of each component in relation to what is happening inside the resistor. This is because the resistor is ohmic and can always provide the time dependent current via Ohm's law simply by dividing the resistor voltage by resistance, $I_{\text{circuit}}(t) = \dfrac{V_R(t)}{R}$.

In the previous graph, the source voltage can be seen as the negative sum of the components' voltages $V_S(t) = -V_R(t) + -V_C(t)$. This is due to the conservation of energy. The source voltage is phase shifted from the resistor voltage by an amount $\phi = \arctan\left(\dfrac{-X_C}{R}\right)$. The π is also included as an additional phase shift, but it is equivalent to multiplying by -1, $\sin(t+\pi) = -\sin(t)$, which emphasizes that electric potential in the circuit is conserved $V_S(t) = -V_R(t) + -V_C(t)$.

Examine the amplitude of the capacitor: $\left(\dfrac{X_C}{Z}\right)$. At very high driving frequency, X_C becomes very small so that the amplitude of the capacitor voltage becomes very small.

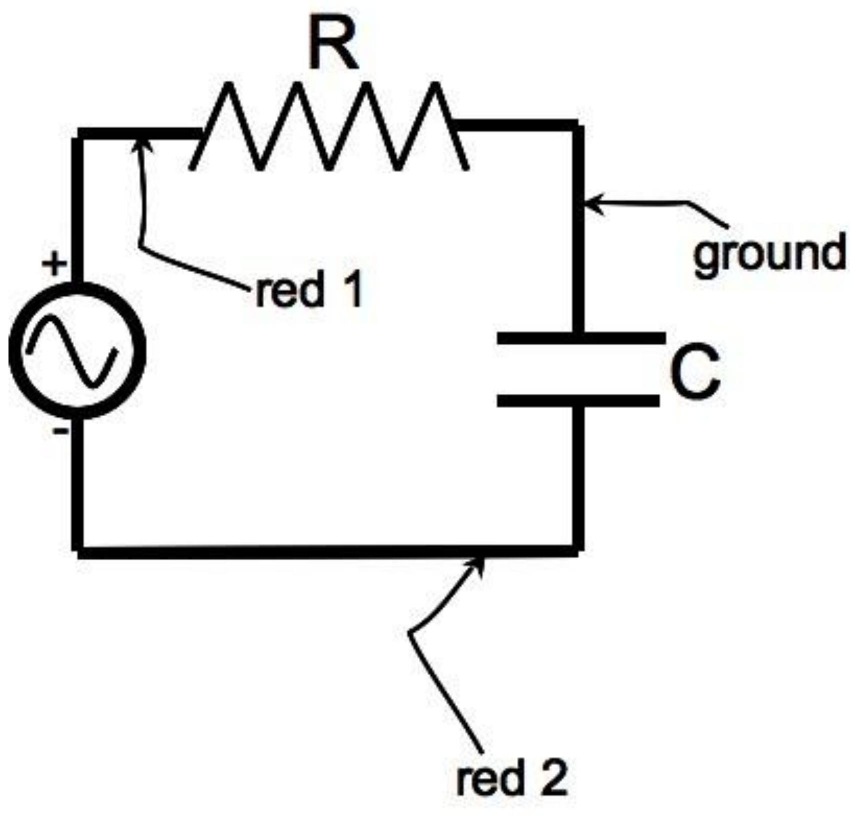
Week 8 Lab: RC Circuit - AC Source

Students Absolutely Must Learn…

- The behavior of a sinusoidally driven system including phase shifts.
- How to use the solutions to the RC circuit driven by a sinusoidal voltage source and what they mean.
- Advanced features of oscilloscopes.

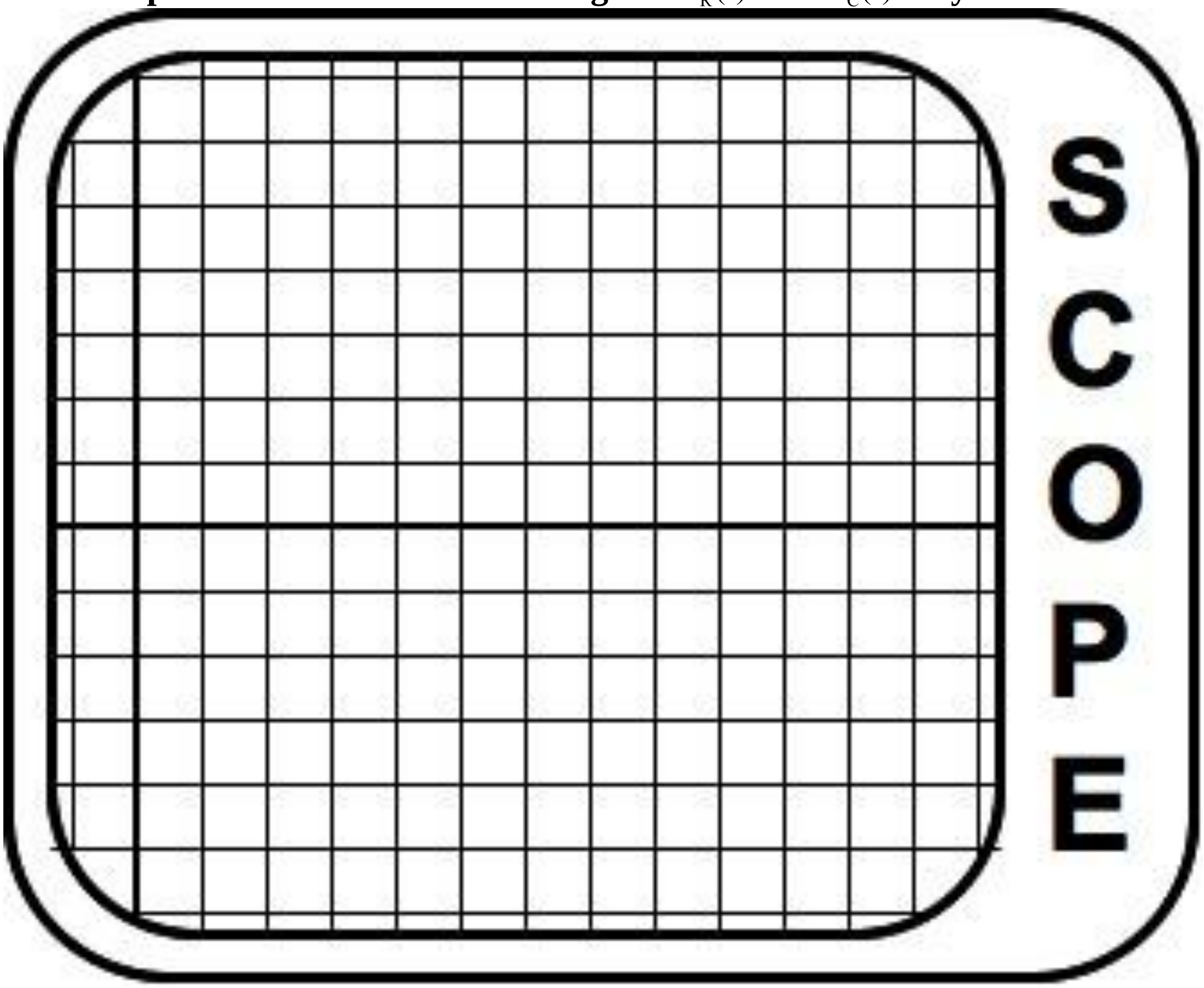
Section 1: examining the components

Set up the sinusoidally driven RC circuit with $R = 10{,}000$ [Ω] , and $C = 1\text{x}10^{-7}$ [F]. Set your function generator to create a sine wave with a voltage amplitude of a nice round number like 3 [V]. You may want to adjust your frequency later, but start at about 400 [Hz]. Set up a middle ground to view the voltages across the resistor and the capacitor simultaneously making sure to invert one of the channels (a necessary step when using a middle ground). Check your setup with other students in the lab.



¿ **1-1**

Make a sketch of the oscillating resistor and capacitor voltages on the oscilloscope screen below. Label the signals $V_R(t)$ and $V_C(t)$ on your sketch



¿ **1-2**

Measure the amplitudes of each signal by measuring the peak-to-peak voltage of each signal.

¿ **1-3**

Use the labeled values to calculate the impedance of your circuit for this driving frequency. $\left(\text{Remember } Z = \sqrt{R^2 + X_C^2}.\right)$**.**

¿ 1-4

Use your previous answer to calculate the amplitudes of the resistor and capacitor voltages, then compare to your measurements to make sure things are as they should be (if not get help).

¿ 1-5

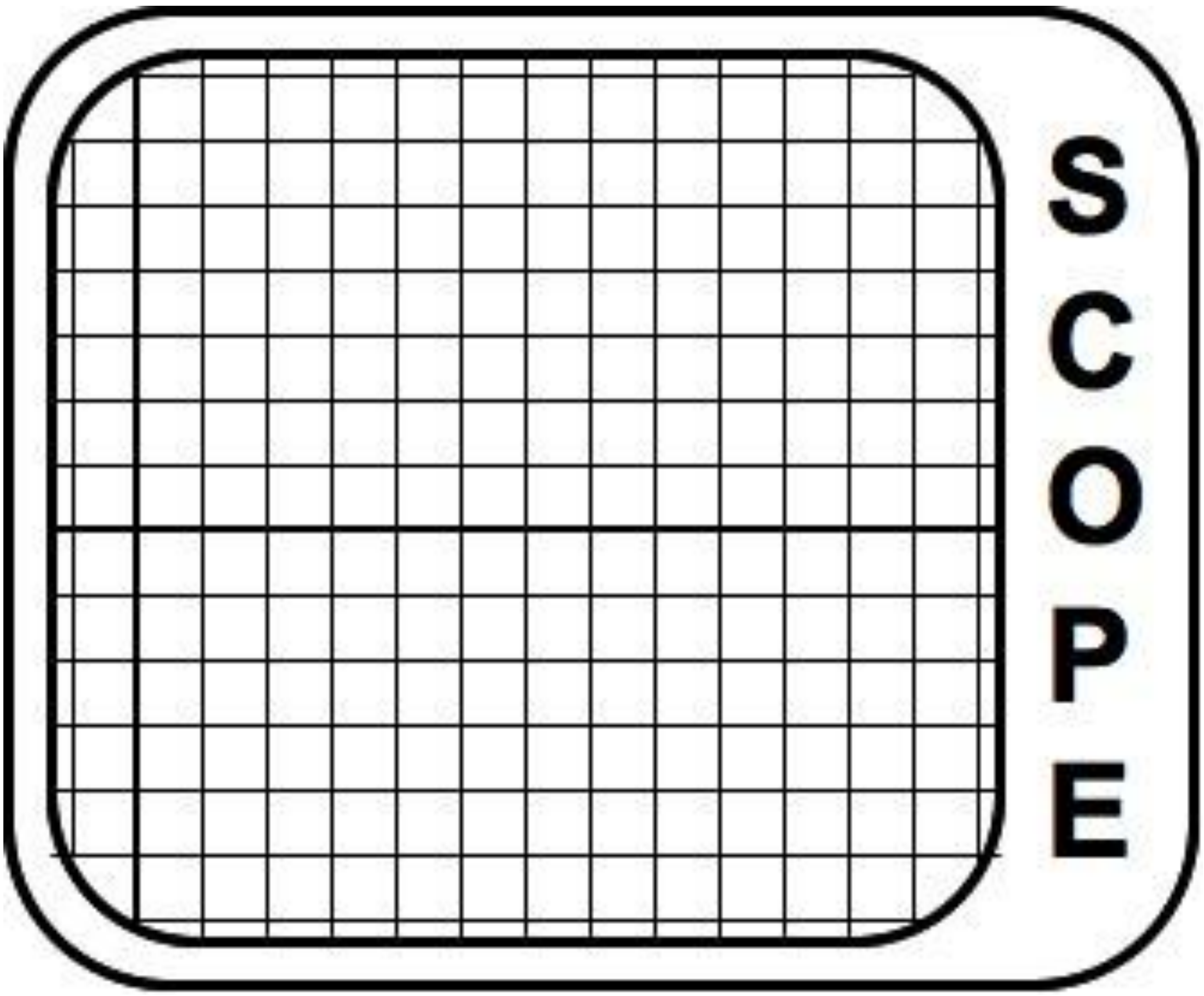
Be sure you are able to use the oscilloscope cursors to double check the driving frequency given by the function generator.

¿ 1-6

Use your answers to the previous questions to write equations for $V_R(t)$, $V_C(t)$ and $V_S(t)$ entirely with numerical values (no free parameters). (Don't forget the phase shifts.)

¿ 1-7

Set your oscilloscope to plot $V_R(t)$ on the x-axis and $V_C(t)$ on the y-axis (an XY plot). Sketch the result on the oscilloscope screen below.



Section 2: experimentally finding the capacitance

Next you will test the relationship $X_C = \frac{1}{\omega_D C}$ by observing a sinusoidally driven RC circuit using many different driving frequencies. Use the same circuit set up as in the previous part of the lab.

¿ 2-1

As you increase the driving frequency, the amplitude of the resistor voltage will increase because the total circuit impedance is decreasing, i.e. $V_{\substack{\text{resistor}\\\text{amplitude}}} = \frac{R}{Z} V_{\substack{\text{source}\\\text{amplitude}}}$. Work through this logic so that you are sure you understand it.

Meanwhile, as the driving frequency increases, the capacitor amplitude decreases. This makes sense because the resistor and the capacitor are the only two components in the circuit other than the source. Since the voltages across both must add up to the source voltage at any instant in time, if the voltage amplitude of one increases, then the other must decrease.

Therefore, there must be some specific driving frequency when the amplitude of the resistor voltage matches the capacitor voltage: $V_{\substack{\text{resistor}\\\text{amplitude}}} = V_{\substack{\text{capacitor}\\\text{amplitude}}}$ for a specific angular driving frequency $\omega_{D,\text{match}}$.

Realizing that $V_{\substack{\text{resistor}\\\text{amplitude}}} = \frac{R}{Z} V_{\substack{\text{source}\\\text{amplitude}}}$ and $V_{\substack{\text{capacitor}\\\text{amplitude}}} = \frac{X_C}{Z} V_{\substack{\text{source}\\\text{amplitude}}}$, setting these two voltages equal when at the matching angular driving frequency $\omega_{D,\text{match}}$ you get $\frac{X_C}{Z} V_{\substack{\text{source}\\\text{amplitude}}} = \frac{R}{Z} V_{\substack{\text{source}\\\text{amplitude}}}$, which simplifies to $X_C = R$. In other words, the voltage across the capacitor equals the voltage across the resistor if their "resistances" are equal, which kind of makes sense. (If not, talk it out with other students or the TA!)

The “single measurement” method for finding the capacitance of an unknown capacitor makes use of the previous equation, $X_C = R$. All you need to do is adjust the driving frequency of your circuit until the capacitor voltage amplitude and the resistor voltage amplitude are equal. Then use $X_C = R$ (substituting $X_C = \frac{1}{\omega_{D,\text{match}} C}$) for the specific $\omega_{D,\text{match}}$ to find the capacitance.

¿ 2-2

Substitute $X_C = \dfrac{1}{\omega_{\mathrm{D,match}} C}$ **into** $X_C = R$**, and then solve for C. Be sure to realize that this equation is only true when the circuit is being driven at the specific frequency $\omega_{\mathbf{D,equal}}$ that makes the resistor and capacitor voltages equal.**

¿ 2-3

Set up a 3 [volts], 400 [Hz] sinusoidally driven RC circuit with $R = 10{,}000\ [\Omega]$ **, and** $C = 1\mathrm{x}10^{-7}\ [\mathrm{farads}]$**. Set up a middle ground to view the voltage across both the resistor and the capacitor simultaneously making sure to invert the correct channel. Adjust the driving frequency until the resistor and capacitor voltages are equal. Then use your formula from 2-2 to find your experimentally determined value for capacitor's capacitance. Remember that the function generator reads the linear frequency.**

The “multiple measurements” method for finding an unknown capacitance is more involved, but more accurate as it involves multiple measurements. The voltage amplitudes of the sinusoidally driven RC are:

$$V_{\substack{\text{resistor}\\\text{amplitude}}} = \frac{R}{Z} V_{\substack{\text{source}\\\text{amplitude}}}$$

and

$$V_{\substack{\text{capacitor}\\\text{amplitude}}} = \frac{\mathrm{X}_C}{Z} V_{\substack{\text{source}\\\text{amplitude}}}.$$

Dividing these two equations gives

$$\frac{V_{\substack{\text{capacitor}\\\text{amplitude}}}}{V_{\substack{\text{resistor}\\\text{amplitude}}}} = \frac{\left(\dfrac{\mathrm{X}_C \cdot V_{\substack{\text{source}\\\text{amplitude}}}}{Z}\right)}{\left(\dfrac{R \cdot V_{\substack{\text{source}\\\text{amplitude}}}}{Z}\right)} = \frac{\mathrm{X}_C}{R}.$$

Therefore,

$$\mathrm{X}_C = R \frac{V_{\substack{\text{capacitor}\\\text{amplitude}}}}{V_{\substack{\text{resistor}\\\text{amplitude}}}}.$$

In order to experimentally determine C for your capacitor, simply combine the last equation with the definition $\chi_C = \dfrac{1}{\omega_{\text{drive}} C}$ and rearrange:

$$\frac{1}{R} \frac{V_{\substack{\text{resistor}\\\text{amplitude}}}}{V_{\substack{\text{capacitor}\\\text{amplitude}}}} = C\omega_{\mathrm{D}}.$$

$$\frac{1}{R}\frac{V_{\substack{\text{resistor}\\\text{amplitude}}}}{V_{\substack{\text{capacitor}\\\text{amplitude}}}} = C\omega_{\text{D}}$$

looks like a weird arrangement for this equation, but if you think of y=mx, then you see that if you graph $\frac{1}{R}\frac{V_{\substack{\text{resistor}\\\text{amplitude}}}}{V_{\substack{\text{capacitor}\\\text{amplitude}}}}$ vs. ω_{D}, you should obtain a linear graph with a slope equal to C.

¿ 2-4

Find C by collecting data for multiple driving frequencies, making a graph on separate graph paper and finding the slope.

Section 3: authentic assessment

¿ 3-1

Quickly set up a working circuit that simultaneously uses a random capacitor and a 1000 Ω resistor *in series* powered by a sinusoidal source voltage on your function generator. Then make the necessary measurements to determine the capacitance of the capacitor. Be sure your experimentally determined measurements give the correct capacitance. Show your results to a student in a different group:

If you are uncomfortable having another student check your work, please ask your TA.

"Yes, I have seen this student find an unknown capacitance 'the easy way'."

Student
Signature:____

Section 4: open-ended

Make a capacitor from the square cardboard pieces covered in conductive aluminum foil. Sandwich a non-foil square of cardboard between the foiled boards, and be sure your makeshift capacitor is not shorted out by accident. Measure the capacitance of your homemade capacitor. The equation for the capacitance of two parallel plates is given by $C = \frac{\kappa \varepsilon_o A}{d}$. Use this equation to report the dielectric constant κ of the sandwiched cardboard between the plates *with correct units*. Note: $\varepsilon_o = 8.85x10^{-12}\ \frac{\mathrm{C}^2}{\mathrm{N}\cdot\mathrm{m}^2}$. Design an experiment to determine the capacitance of your cardboard capacitor and the dielectric constant of the cardboard.

You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the following page.

¿ 4-1
hypothesizing/planning:

¿ 4-2
observations/data:

¿ 4-3
calculations/conclusion

I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: ____**

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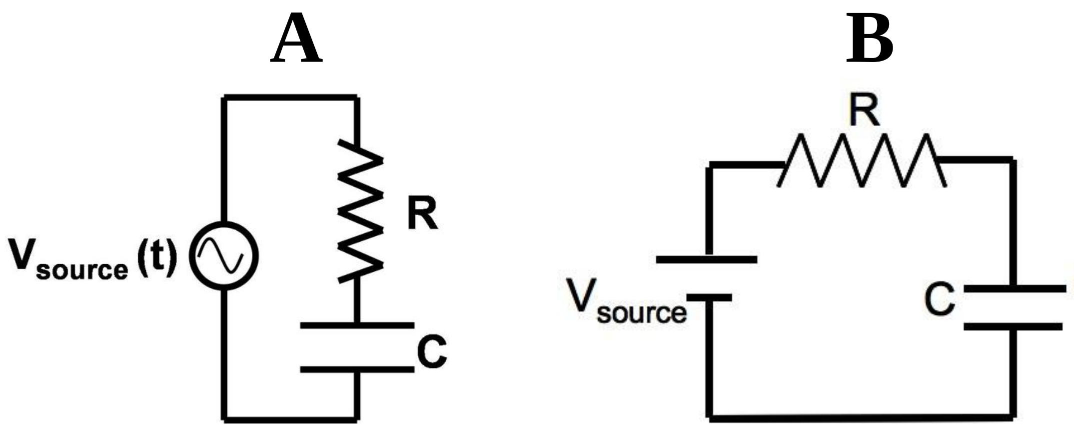
Week 8 Take-Home Quiz

Score:__________ /5

¿ THQ-1 (3-points)

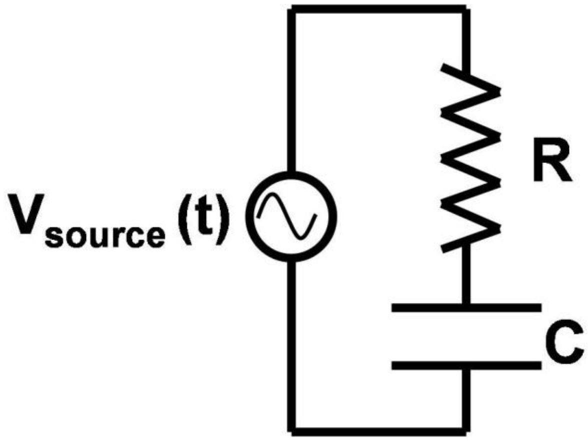


a) Which capacitor circuit(s) has time dependent resistor and capacitor voltages, *A*, *B* or *Both*?

b) Which capacitor circuit(s) has resistor and capacitor voltages that are exponential in time, *A*, *B* or *Both*?

c) Which capacitor circuit(s) has resistor and capacitor voltages that are sinusoidal in time, *A*, *B* or *Both*?

¿ **THQ-2 (2-points)**



For the above sinusoidally driven circuit, $C = 7\text{ x}10^{-8}\,[\text{F}]$ **and** $R = 7{,}000\ [\Omega]$**. At what driving frequency f_D would you find the resistor and capacitor voltage amplitudes to be equal?**

Unit 5 Lab Report Instructions

Unit Lab Report [40 points]

Use the following section titles in your report. Images, text or equations plagiarized from the internet are not allowed! Remember to write your report *alone* as collaborating with a lab partner will make you both guilty of plagiarism. **Please label your lab report sections:**

- **Title [0 points]** – A catchy title worth zero points so make it unique and fun.
- **Mini-Report [10 points]:** ***{4-5 paragraphs, ~2 double-spaced pages}***
  Choose **one** of the following sections about which to write your mini-report:
  Week 9 Section 2 or Week 10 Section 3
  Write a "mini-report" for one particular section of the lab manual. Describe what you did succinctly, and then what you found accurately. Then explain what the result means and how it relates to some of the concepts in the previous section. *You must write using sentences & paragraphs; bulleted lists are unacceptable.* ***Please label your mini-report sections:***
  - **Abstract:** Write 2-3 sentences about the goals of this section. Describe the concepts you were investigating and how the experimentation you performed allowed you to investigate these concepts. Write 2-3 sentences summarizing the procedure. Write 2-3 sentences summarizing the results and what the results mean with regard to the concepts you were investigating. *It is best to write the abstract last*.
  - **Procedure:** Do not provide a lot of specific details, but rather you should summarize the procedure so that a student who took the course a few years ago would understand what you did.
  - **Results:** Provide a description of the data you obtained such as data tables. Restate any measured values, calculated slopes of lines-of-best-fit, etc. Do not *interpret* your results, save any interpretation for the discussion.
  - **Discussion:** Analyze and interpret the results you observed/measured in terms of some of the concepts and equations of this unit. It is all right to sound repetitive with other parts of the report.
- **Open-Ended Discussion [10 points]** – ***{1-2 paragraphs, ~1 page double-spaced}*** Choose **one** of the open-ended experiments from the two weekly activities to write about. Describe your experimental goal and the question you were trying to answer. Explain the ideas you came up with and what you tried. If your attempts were successful, explain your results. If your attempts resulted in failure, explain what went wrong and what you would do differently in the future. *You must write using sentences & paragraphs; bulleted lists are unacceptable.*
- **Graphs [5 points] - {attach to your typed report}** Graphs must be neatly hand-drawn <u>during lab</u> on graph paper. Your graphs must fill the entire page (requires planning ahead), include a descriptive title, labeled axes, numeric tic marks on the axes, and unit labels on the axes. If instructed to calculate the slope of the line-of-best-fit, write it directly on the graph.
  Week 9: none
  Week 10: 5-4
- **Take-Home Quizzes [2x5 points = 10 points] - {attach after your Graphs}**
- **Selected Worksheet Pages [5 points] - {attach after your Take-Home Quizzes }**
  Your TA will choose which pages you need to hand in.

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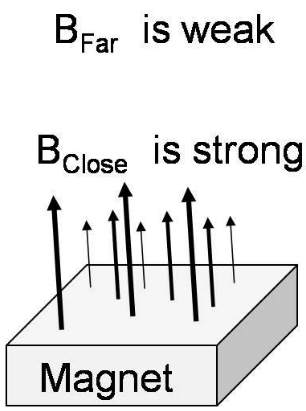
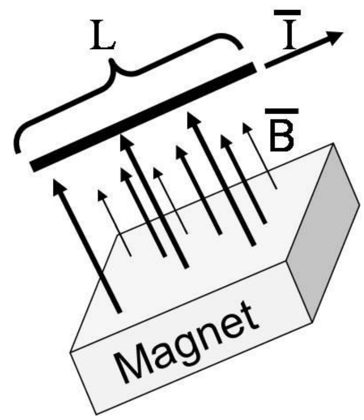
Week 9 Pre-Lab: Motors

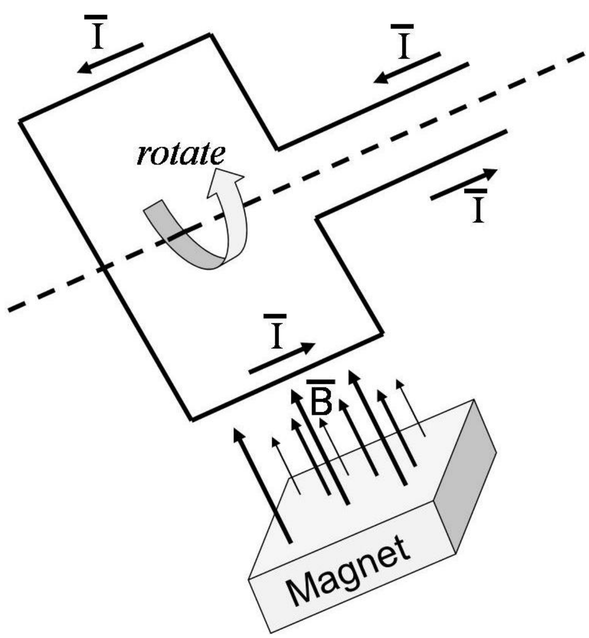
A magnet has a strong magnetic field near its surface, but this field becomes very weak away from the magnet surface. When a current carrying wire of length L passes through a magnetic field, the magnetic field provides a force **on the wire** given by $\vec{F}_{\text{from B–field}} = L \cdot \vec{I} \times \vec{B}$. The force on the wire above is out of the page as determined by the right hand rule.



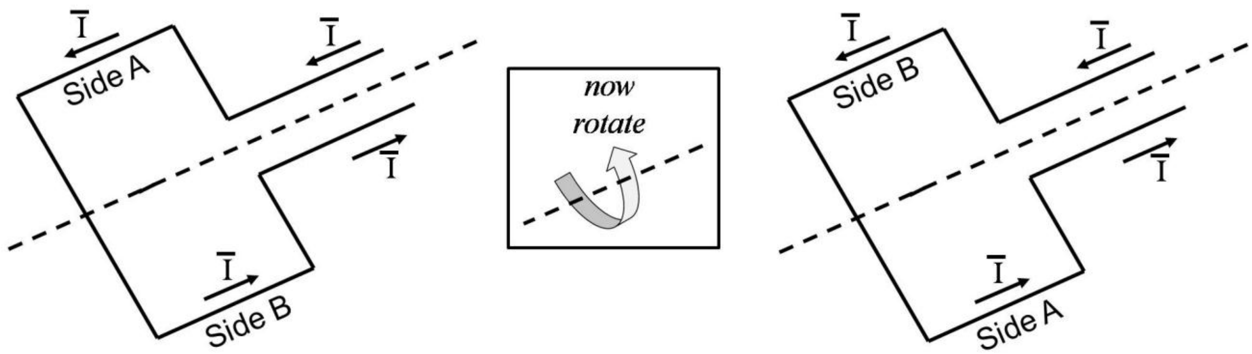


Note that **I** is written as a vector to describe the direction of the current, and the cross product indicates that the right hand rule must be used to find the direction of the force.

You can use this simple concept to make the real motor. The motor is made of current carrying wire loops that can rotate about an axis shown as a dashed line in the picture below. The part of the wire loop that passes through the magnetic field experiences a magnetic force upon it. This magnetic force causes a net torque on the wire loop yielding angular acceleration. The wire loop will therefore rotate faster and faster until the torque from the magnetic force equals any frictional torque in the motor. At this time, the loop will reach a constant angular speed ω.

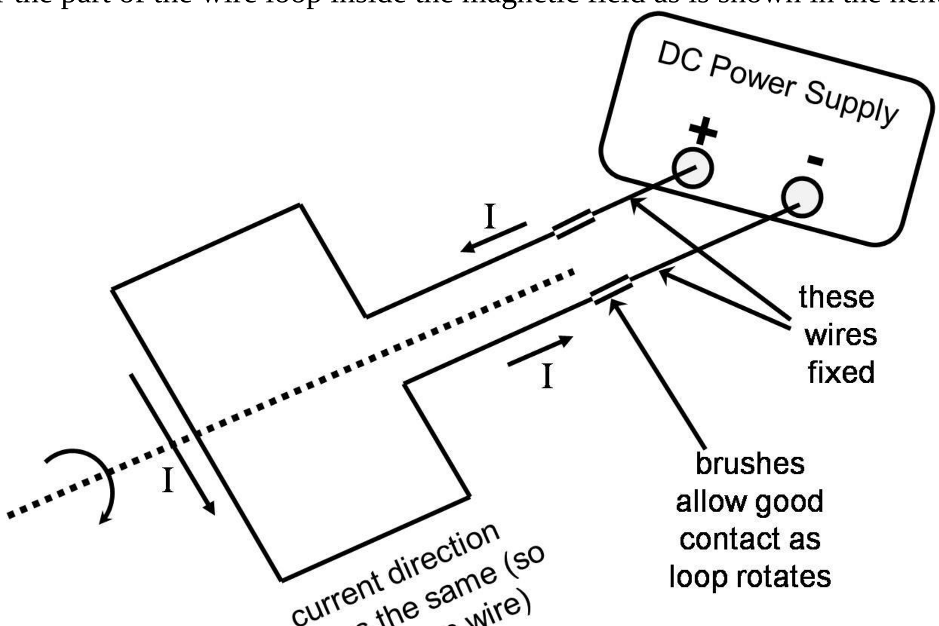


The only difficulty in making a motor is to ensure that the current always travels in the same direction as it passes through the magnetic field no matter how the loop itself is oriented. Examine the following picture to better understand what this difficulty is if the current supplied to the wire loop is always the same for each lead of the wire loop:



In this before-and-after picture, you can see that when the wire loop rotates 180^o the force will now push the loop in the opposite direction because the direction of the current through the magnetic field will be reversed. Unless you want to make a fancy electronic rocking chair, this is not good motor design.

Instead, you will need to design your motor so that the current always flows in the same direction for the part of the wire loop inside the magnetic field as is shown in the next picture:



In this motor set-up, when the wire loop rotates 180^o, the manner in which current is supplied to the loop is changed in order to get the current to flow in the same direction for the part of the loop experiencing the magnetic force.

Week 9 Lab: Motors

Students Absolutely Must Learn…

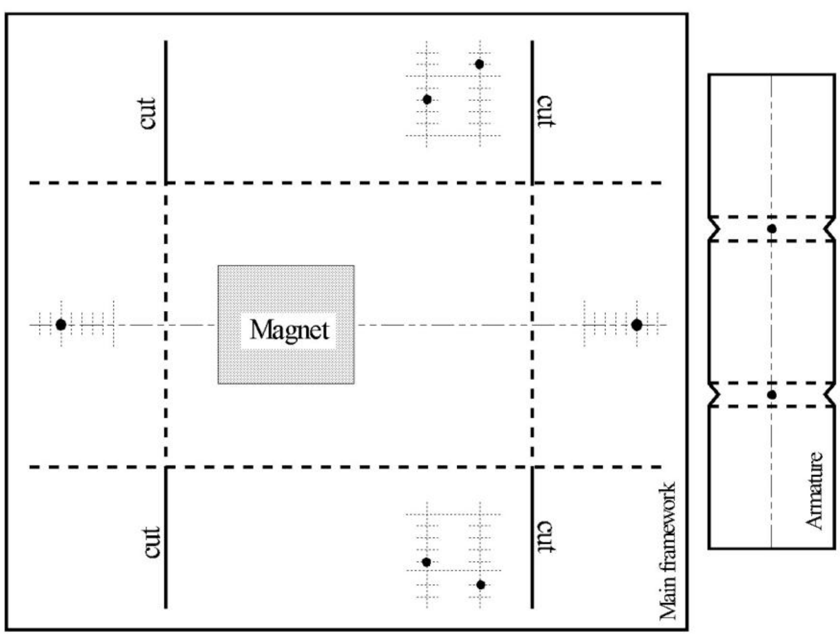
- How motors work:
  - Lorentz force law for wires.
  - Brush contacts.
- How generators work.
- Skill working with wire.
- How to measure power being consumed by a motor.
- Advanced features of oscilloscopes.

Section 1: constructing the motor

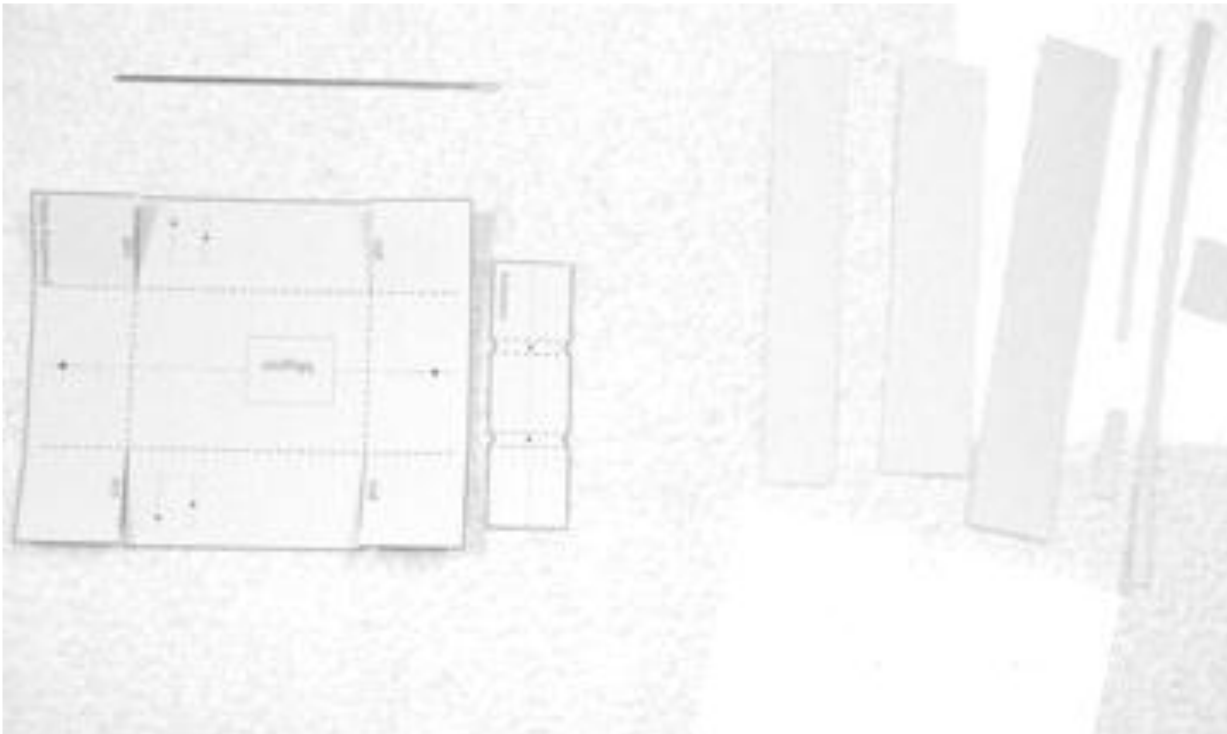
! The wire's insulation melts at approximately 5 amps of intermittent current (depending on applied voltage). Once the insulation melts, all the motor loops are shorted out so that you only have one loop to drive the motor (i.e., the motor is ruined).

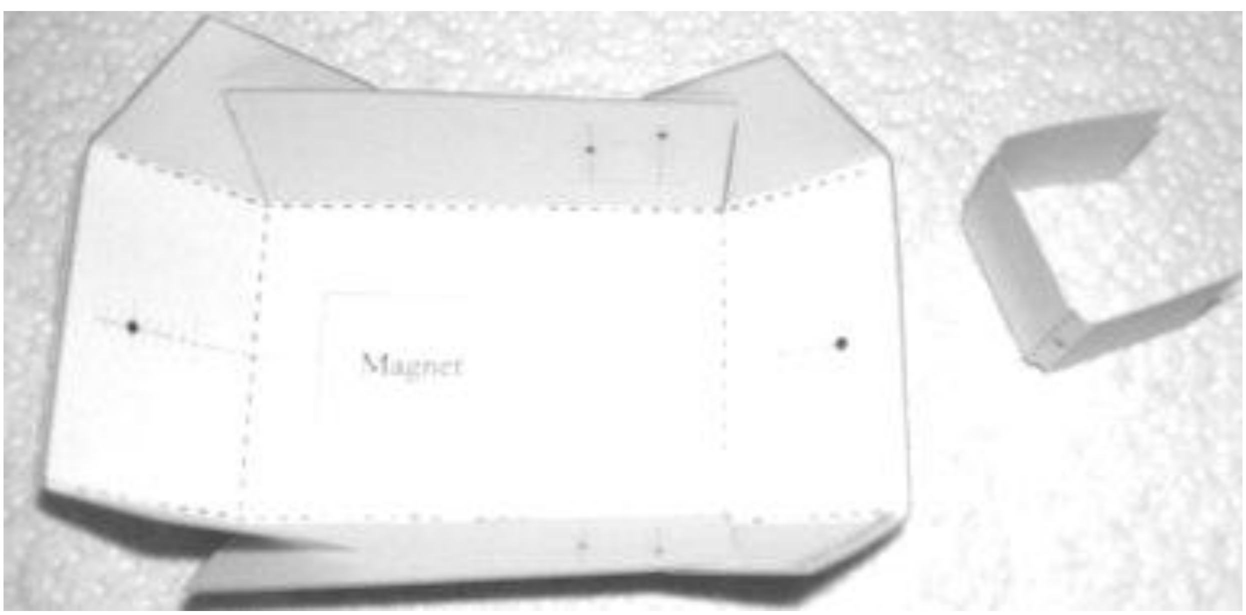
- **Do not use too large of an input power.**
- **Do not let the motor get stuck with current flowing through its nearly resistanceless wires. (Otherwise the wires are the only resistor in the circuit and become very hot.)**
- **If the motor stops spinning, IMMEDIATELY shut off the voltage supply or your motor will begin to turn into a gaseous state!**

1) Begin with your card. Write your name on the card by the box containing the word “magnet”.

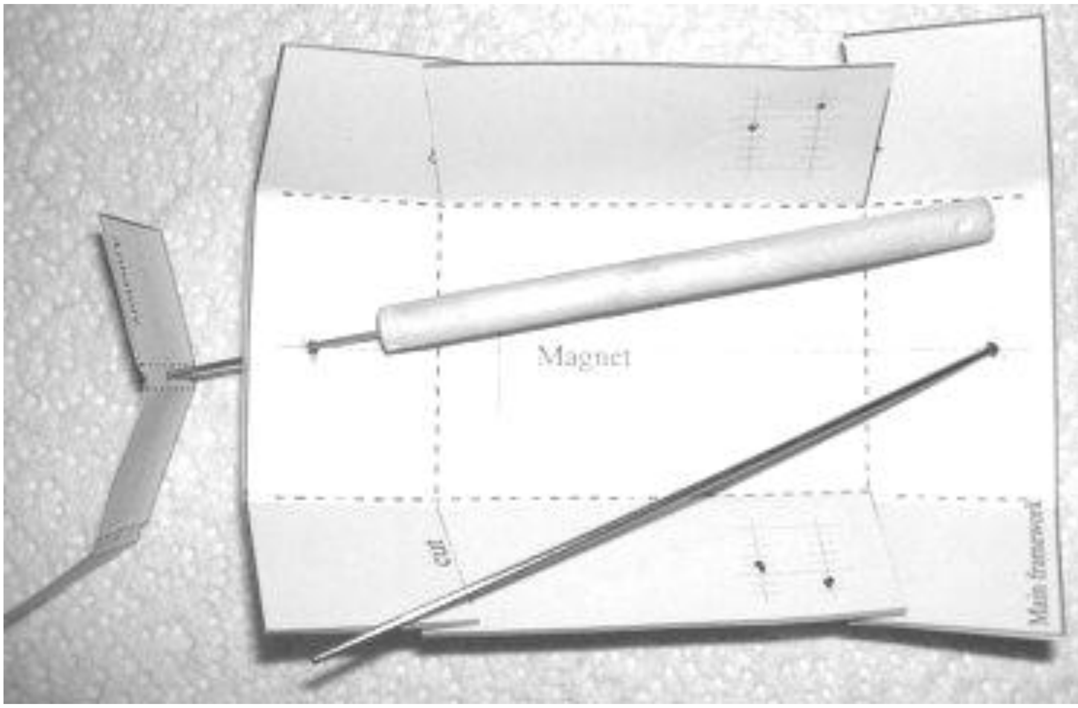


2) Cut along the solid lines and fold along the dotted lines. Taking your time to make things nice in the motor construction will ensure your motor runs well and is easily fixed if it breaks down.

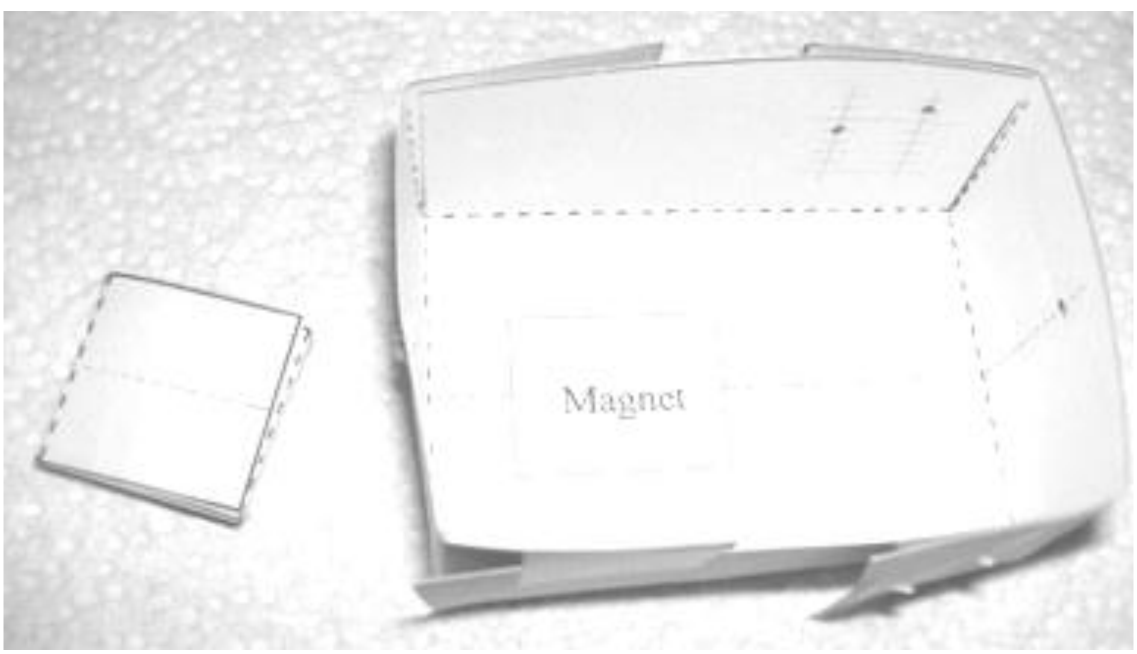




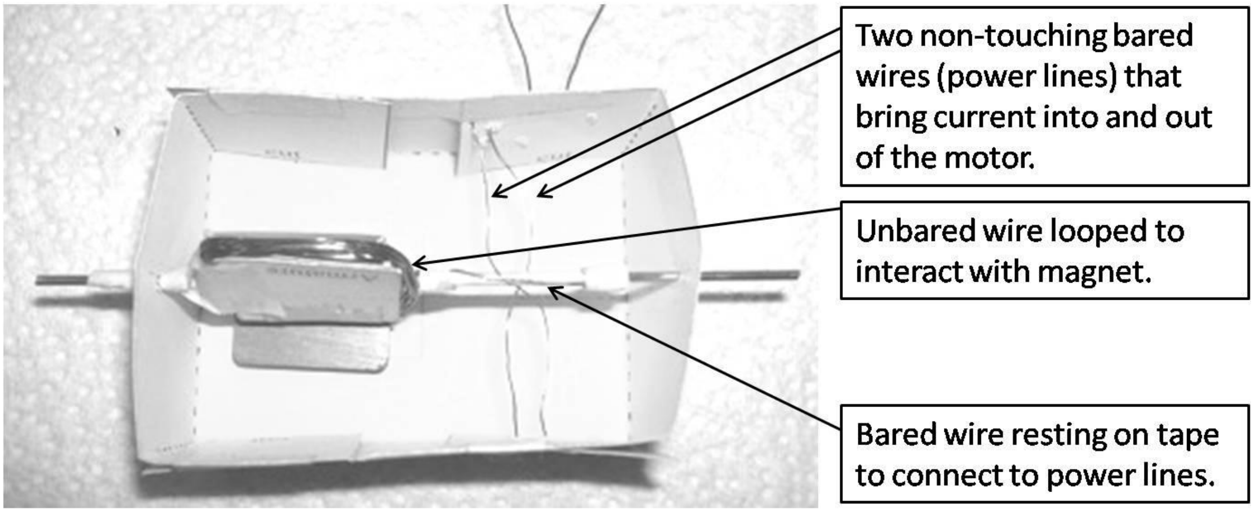
3) Carefully use a sharp poker to poke out the marked black dots. Wiggle the two axial dots so that the motor axis will turn easily (with low friction). **Never poke through the paper with your finger on the other side. Always lay the paper flat over the magnet and use the magnet's hole to poke holes in your paper.**



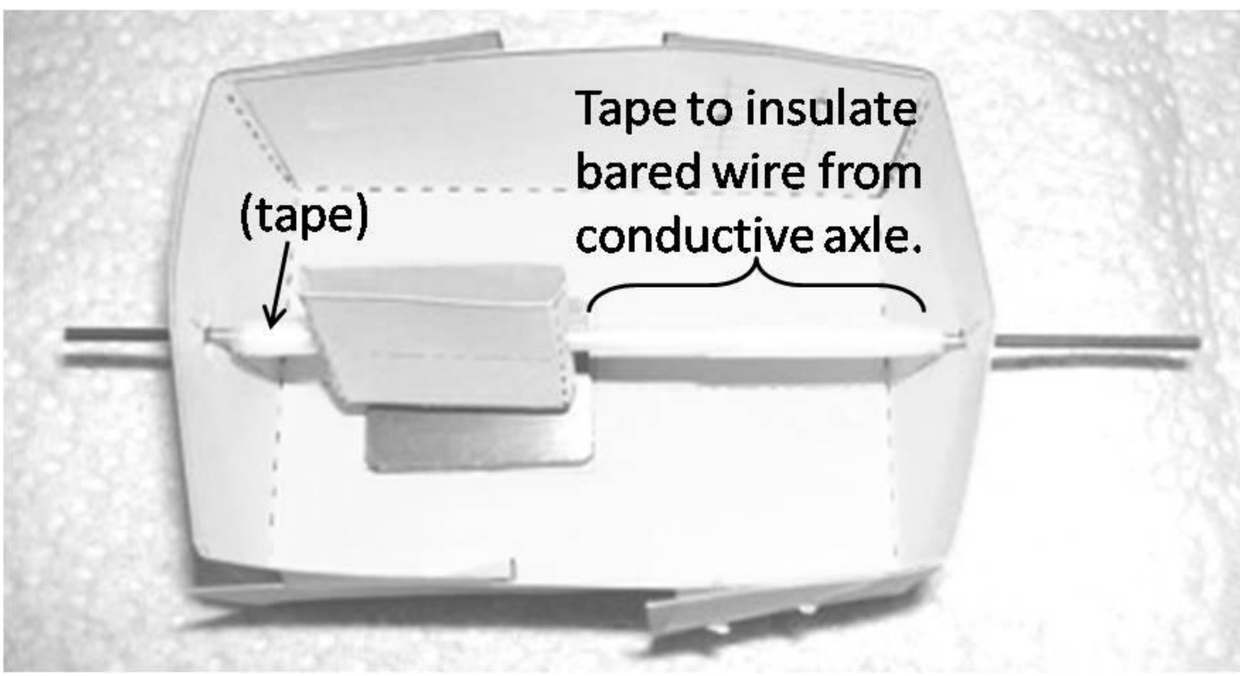
4) Use masking tape or clear tape to tape up your motor-enclosure box and armature box.



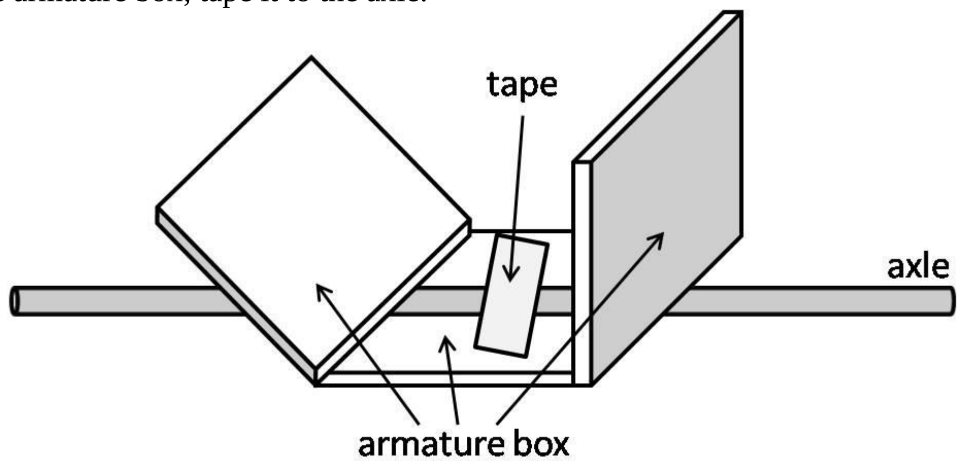
5) At this point, examine what a finished motor should look like.



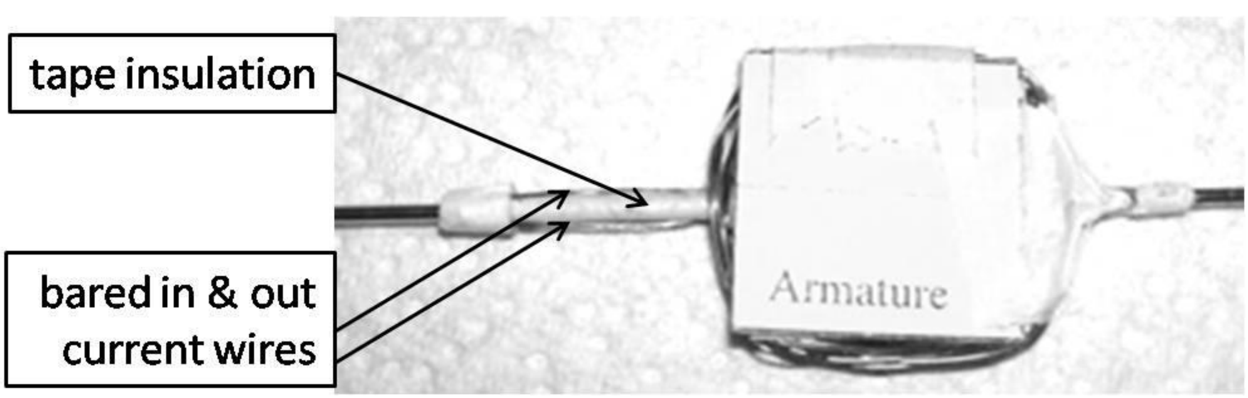
6) Tape your magnet into your box, and add tape to the axle rod. The tape in the axle rod serves the dual purpose of insulating wires from the metal rod as well as keeping the rod positioned correctly in the motor-enclosure box: so the armature box stays above the magnet. Pay careful attention to locate the insulating tape on the correct location of the rod by repeatedly placing the rod into the motor-enclosure box and spinning it with your fingers.



7) Add some tape as neatly as possible to affix the axle rod to the armature box, or before closing the armature box, tape it to the axle.

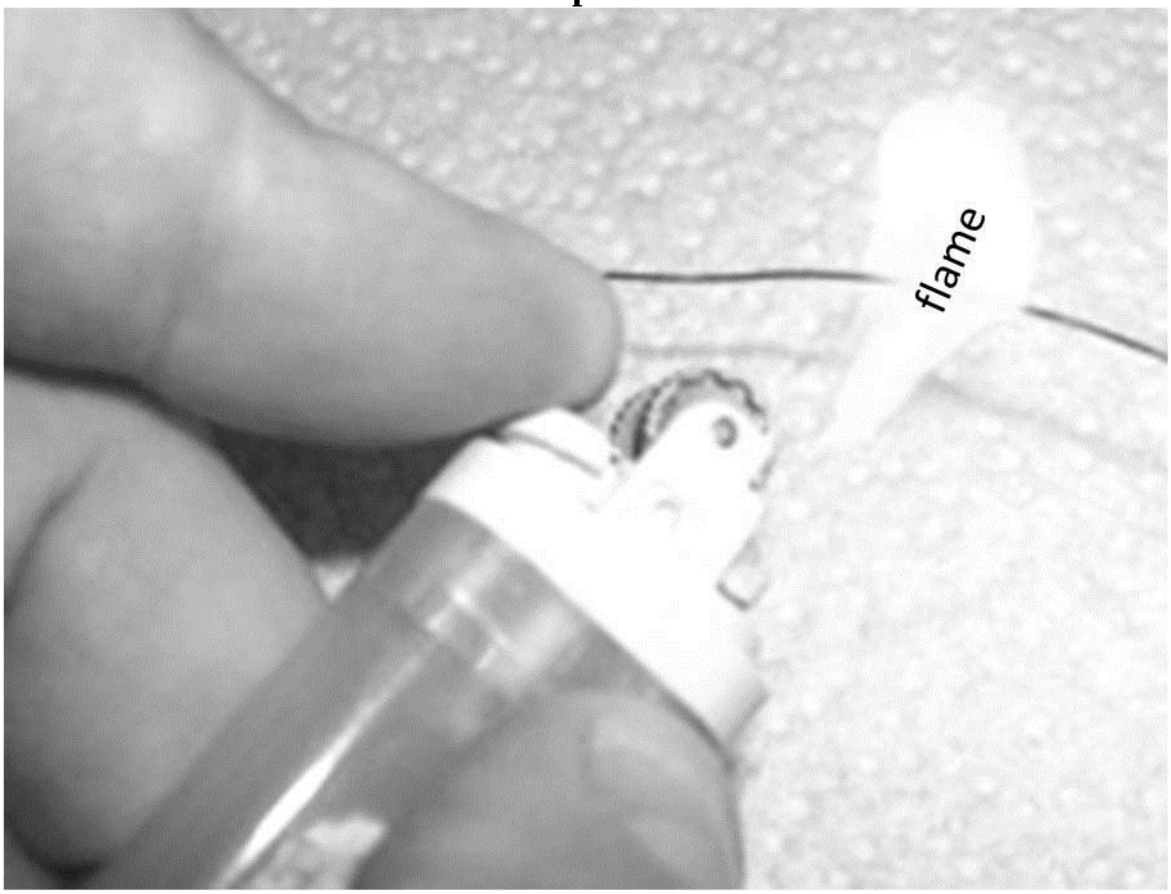


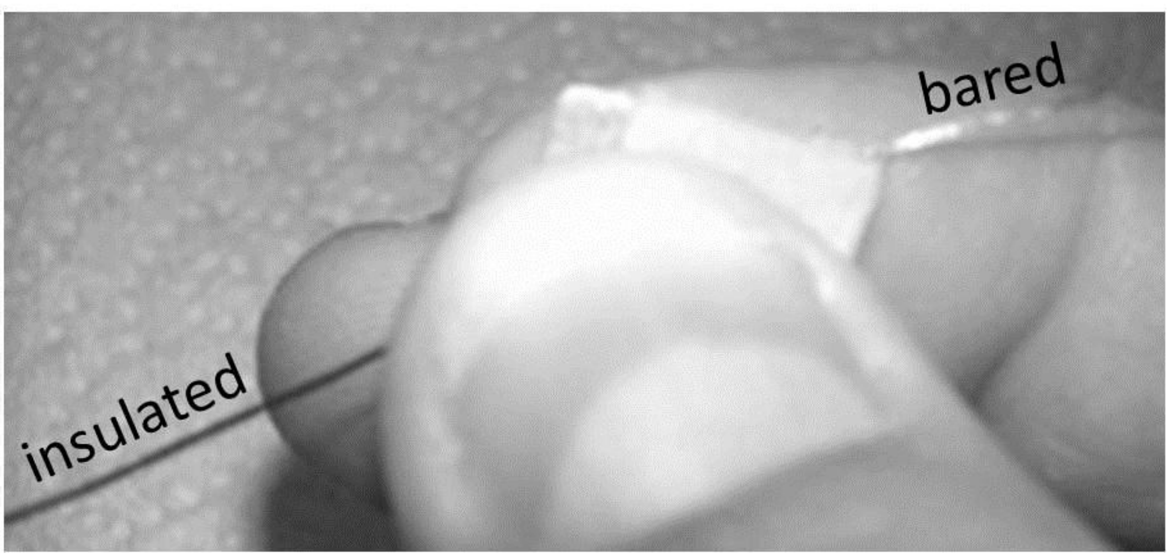
8) Take ~2 meters of wire and wrap the armature box. Both ends of the wire should protrude from the winding box along the axle insulation. You will eventually bare the two ends and tape them down to the axle, but leave them free until you learn how to bare the wires. Notice that the two ends of the winding protrude to the left of the armature box and are taped down **flat against the axle** and **in the place of the armature box**. If the leads are not in the plane of the armature box, the coil will receive current when the coil is 90^{o} rotated away from the magnet (not good).



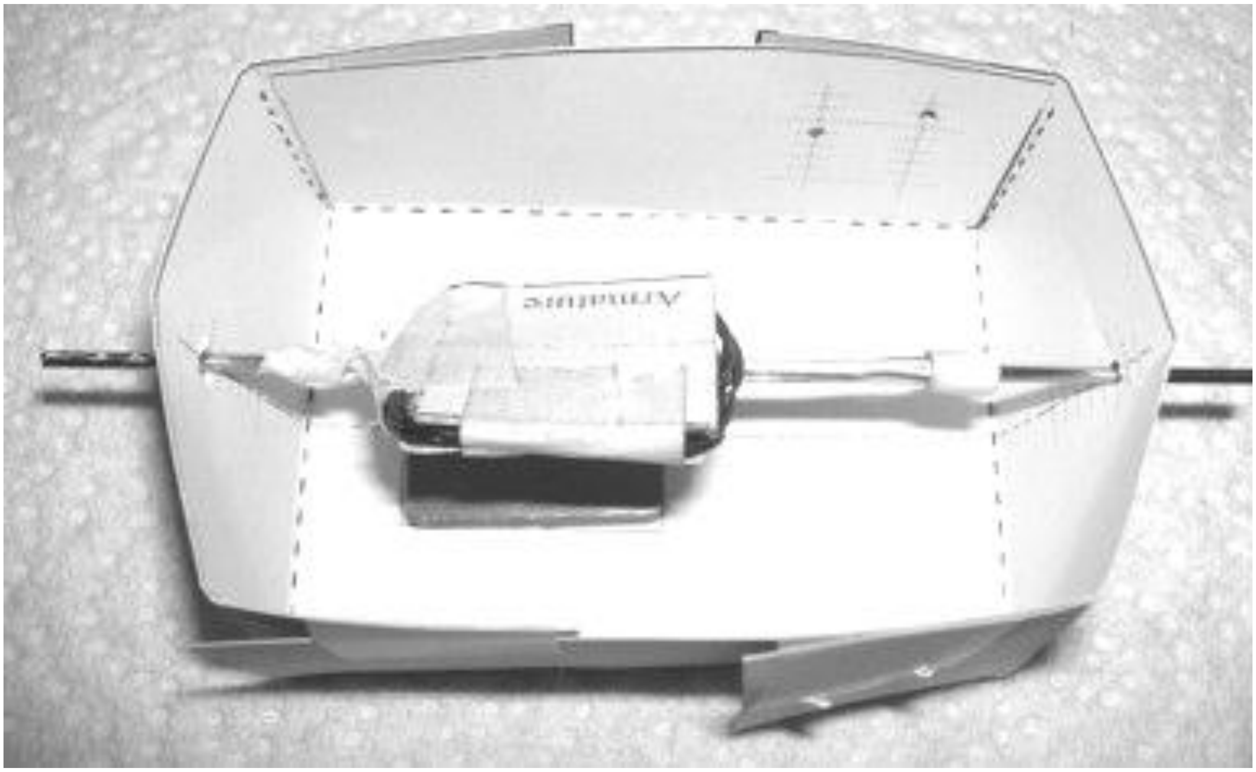
9) Wherever good electrical contact is desired, the colored insulation must be burned and sanded off that part of the wire so that clean, bright copper can be seen. To bare the wire you must burn off the insulation along the part of the wire you wish to bare. Burn the insulation thoroughly; it will appear blackened. Then use sandpaper to clean the charred wire insulation and leave a nice bright, bared length of copper wire.

! Do not sand the finish off the table tops!

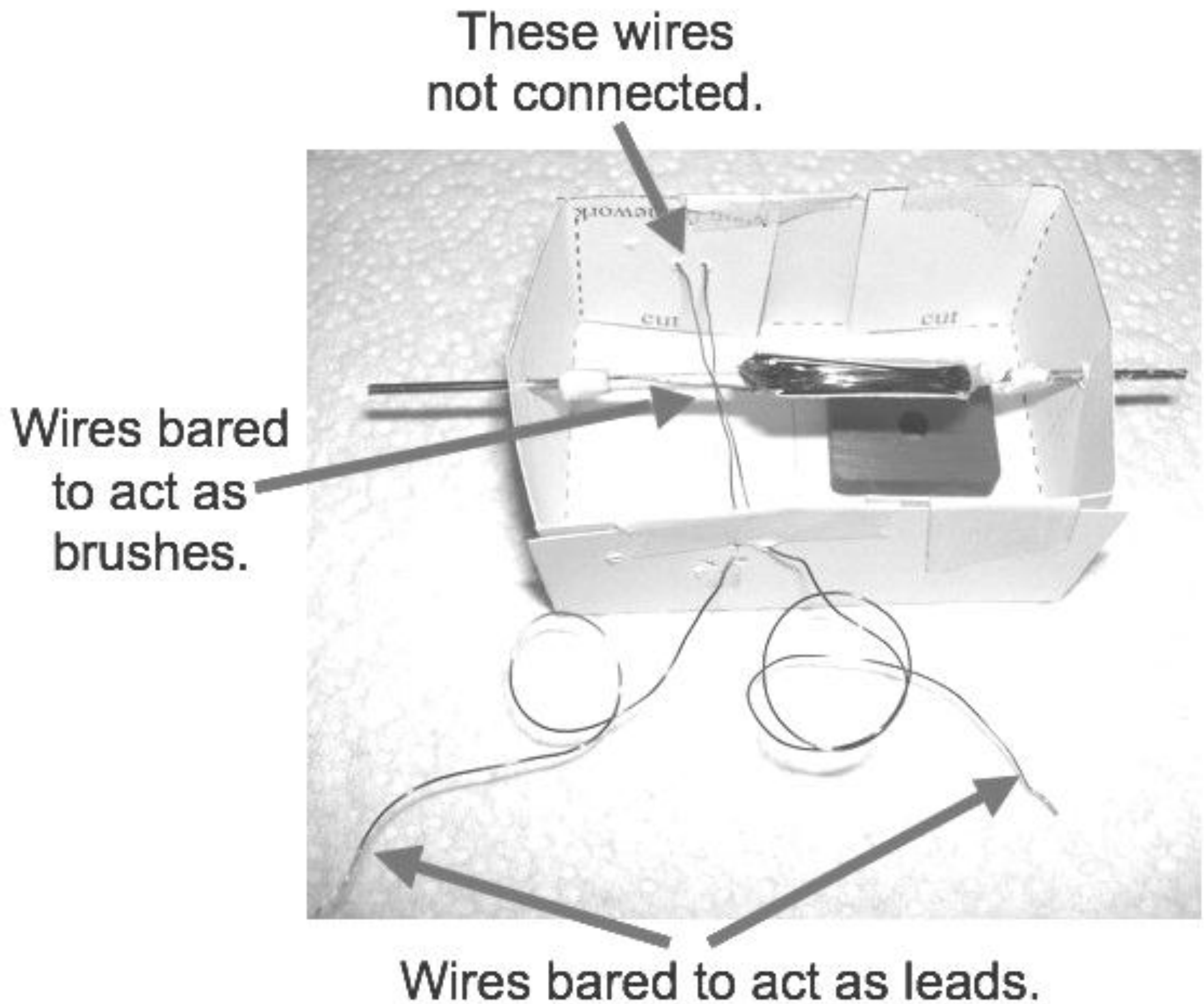




10) Place the axle into the motor-enclosure box. You may eventually need to add tape to other parts of the axle in order to keep the axle from shifting around too much in the motor-enclosure box during operation.



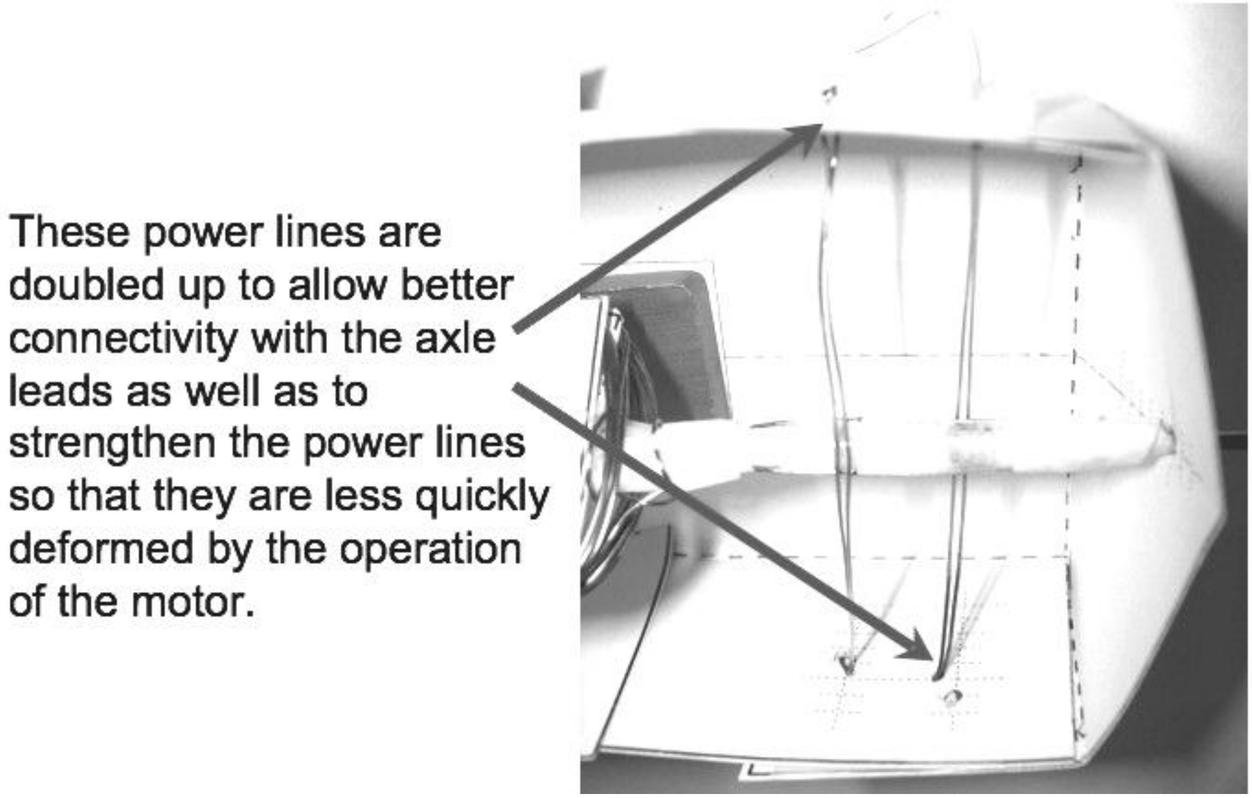
11) Finally you must insert two bared wires to act as brushes for your motor. These "power lines" are the most difficult part of the motor to get correct. The axle leads must make **precise** contact with these power lines as the motor turns. Motors that work best tend to have very straight brushes that lie tightly against the axle. Note that the location of the power lines (the punched holes in the sides of the motor-enclosure box) may need to be changed depending on the final position of your axle leads.



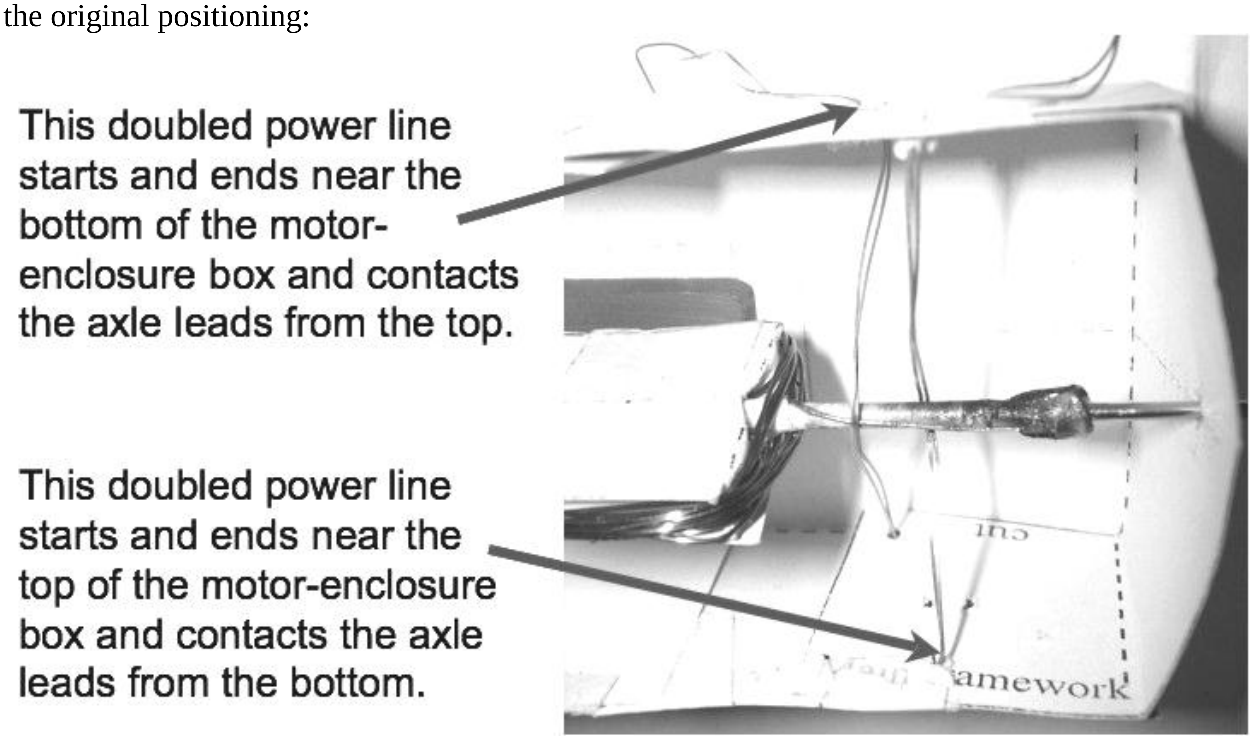
(*See the next page for power line hints.*)

Note on testing your motor:
Always start with low voltage (~2 Volts) when connecting your motor to the DC power supply. Then start the motor by spinning it with your fingers. You should be able to *feel* with your fingers which way the motor is being pushed to rotate. This will tell you which way to spin it. You may have to keep increasing the supply voltage to keep your motor spinning. Never let your motor stay connected to the source with current running through it when it is not spinning because the insulation will rapidly melt away. **(You will hear the TA shouting from time to time during this lab, "Unhook it! Unhook it!")**

Other power line configurations have shown improvement over the original design. One idea is to double up the power lines so that they make better contact and are more durable:



Another idea is to change the location of the power lines so that they “hug” the axle more than in the original positioning:



Section 2: making measurements

Power & Efficiency

At some time as the motor rotation rate speeds up, the angular speed ω reaches an equilibrium value where the opposing torques balance the torque caused by the magnetic force, $\vec{T}_{\substack{\text{from}\\ \text{B-field}}} = \sum \vec{T}_{\text{opposing}}$. These opposing torques come from friction and any load you place on the motor (work you make the perform). In this experiment, it will be difficult to directly analyze the magnetic force being applied to the motor so that the force-torque perspective will not be useful. Therefore, it is better to examine the energy perspective of the motor.

Conservation of energy indicates that power in must equal power out:

$$P_{\substack{\text{input}\\ \text{power}}} = P_{\substack{\text{output}\\ \text{power}}} + P_{\text{friction}}.$$

Thinking of the motor as any other circuit component, we know that the electrical power being used by the component is P=IV. So the input electrical power can be measured in the lab as

$$P_{\substack{\text{input}\\ \text{power}}} = I_{\substack{\text{through}\\ \text{motor}}} V_{\substack{\text{across}\\ \text{motor}}}.$$

The output power is equal to the rate of work energy that the motor performs per second,

$$P_{\substack{\text{output}\\ \text{power}}} = W_{\substack{\text{by motor}\\ \text{on environment}}} / \Delta t.$$

Since work is given by

$$W_{\substack{\text{by motor}\\ \text{on environment}}} = \vec{F}_{\text{on object}} \bullet \vec{d}_{\substack{\text{object}\\ \text{travels}}},$$

this is easy to calculate if the motor were to be lifting an object vertically upward since in this case

$$\vec{F}_{\substack{\text{on object}\\ \text{by motor}}} = -\vec{F}_{\substack{\text{on object}\\ \text{by gravity}}} = -m_{\text{object}}\vec{g}$$

so that

$$W_{\substack{\text{by motor}\\ \text{on environment}}} = -m_{\text{object}}\vec{g} \bullet \vec{d}_{\substack{\text{object}\\ \text{travels}}} = mgd.$$

But *mgh* is the familiar formula for gravitational potential energy, so we know we are doing things correctly.

Of course, $I_{\substack{\text{through}\\\text{motor}}}$ or $V_{\substack{\text{across}\\\text{motor}}}$ may not be constant as the motor operates, but we can treat these as average values for now. Also, the motor will not always be able to make contact through the wire brushes so that current does not flow to the motor at all times. If the motor is only in contact with the source for 30% of the time, then

$$P_{\substack{\text{input}\\\text{power}}} = 0.3 \cdot I_{\substack{\text{through}\\\text{motor}}} V_{\substack{\text{across}\\\text{motor}}}.$$

The oscilloscope in the lab is very useful in determining what percentage of the time current is flowing through the motor.

¿ 2-1

A motor is 'on' 50% of the time at 4 [V] and 0.03 [A]. It lifts a 0.02 [kg] of paper clips upward 0.8 [m] in 6 [s]. Calculate the electrical power going into the motor, the power output by the motor as work, and the power lost as friction.

In order to measure the current through the motor, a rather imprecise value is obtained from the power supply readout. A much better value for the current may be obtained by placing the motor in series with a 1 Ω resistor and using the oscilloscope to find the current through the resistor (and therefore the motor). (Remember to get the current in the resistor by measuring voltage and dividing by R.)

The efficiency of the motor is given by $\varepsilon_{\text{efficiency}} = {P_{\substack{\text{output}\\\text{power}}}} \big/ {P_{\substack{\text{input}\\\text{power}}}}$. If the motor is made to lift objects vertically, then the output power can be found via the force of gravity: $E_{\text{output}} = mgh$ so that $P_{\substack{\text{output}\\\text{power}}} = \frac{\Delta E_{\text{output}}}{\Delta t} = mg\frac{\Delta h}{\Delta t}$.

¿ 2-2

Calculate the efficiency of the motor from the previous question.

Speed of Rotation

The rotational speed of a motor is typically measured in revolutions per minute [RPM]. You will need to use the oscilloscope to find the time of one full oscillation (the period), turn this into frequency, and finally into RPMs. Use simple factor labeling to do this:

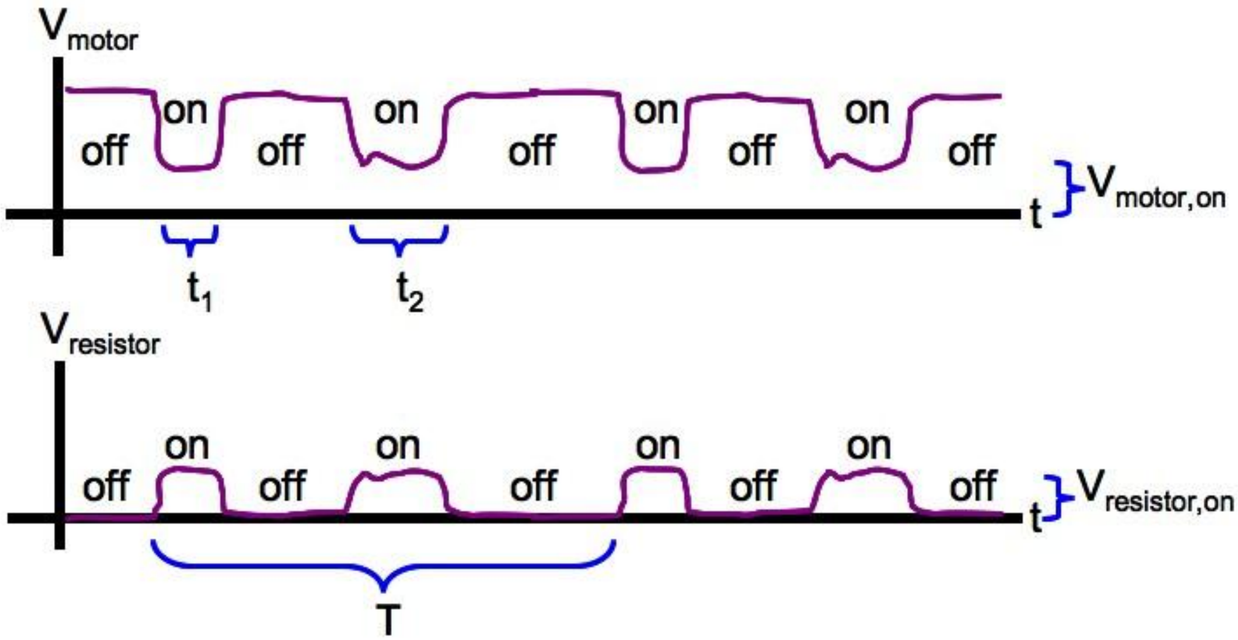
$$f\left[\frac{\text{cycles}}{\text{seconds}}\right]\cdot 60\left[\frac{\text{seconds}}{1\,\text{minute}}\right]=60\,f\left[\frac{\text{cycles}}{\text{minute}}\right]\ \text{or}\ 60\,f\left[\frac{\text{revolutions}}{\text{minute}}\right]\ \text{or}\ 60\text{f}\ \ [\text{RPMs}].$$

¿ 2-3

A motor turns once in 0.02 [s], how many RPMs is it rotating at?

Observing the Motor Parameters

The easiest way to observe the behavior of the motor is with a middle ground measurement between a 1 Ω resistor and the motor in series. This will provide the following graph on the oscilloscope screen, though it may take some effort to find the correct time scale. The percent of time that the motor is on is simply (t_1+t_2) / T. Using the run/stop button to collect data from the oscilloscope is useful for this because the triggering will be very sensitive and the will continuously lose the signal.



¿ 2-4

In the previous picture, why is the voltage across the motor equal to the source voltage when the motor is off? You may want to explain with circuit diagrams.

Later in the lab you will need to measure these two components (motor and resistor) simultaneously in order to calculate the RPMs and the power. Since

$$\begin{aligned} P_{\text{motor,on}} &= I_{\text{motor,on}} \cdot V_{\text{motor,on}} \cdot (\text{fraction of time motor is on}) \\ &= I_{\text{resistor,on}} \cdot V_{\text{motor,on}} \cdot (\text{fraction of time motor is on}) \\ &= \frac{V_{\text{resistor,on}}}{\text{R}} \cdot V_{\text{motor,on}} \cdot (\text{fraction of time motor is on}) \end{aligned}$$

you can obtain the power used by the motor (friction) using only the pictured measurements.

Section 3: authentic assessment

Always start with low voltage (less than 2 [V]) when connecting your motor to the DC power supply. Then start the motor by spinning it with your fingers. You should be able to *feel* with your fingers which way the motor is being pushed to rotate. This will tell you which way to spin it. You may have to keep increasing the supply voltage to keep your motor spinning. Never let your motor stay connected to the source with current running through it when it is not spinning because the insulation will rapidly melt away.

¿ 3-1

Show your TA that you can successfully build a working motor. Note: if someone is stuck, please give them advice!

"Yes, I have seen this student build a motor that successfully runs (on electrical input power). This will be an indispensible skill should they find themselves lost at sea!"

! **TA signature: ____**

~~Student Signature~~:____

Section 4: open-ended

Imagine you wish to sell your motor on Ebay. You will need to describe as many of your motor's features in addition to your own intense emotional attachment to your motor. Design a way to calculate the minimum source voltage required to operate your motor $V_{source,min}$ and the RPMs at this minimum voltage. Also find and the power loss due to frictional torque $P_{motor,on}$. Note that you cannot obtain an accurate measure of voltage or current with the built-in source meters so must use the oscilloscope to find these values as shown in section 2. Also you should report the maximum safe source operating voltage $V_{source,max}$ and corresponding RPMs your motor can operate safely at (but don't find $RPM_{MotorFailure}$).

You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the next page.

¿ 4-1
hypothesizing/planning:

¿ 4-2
observations/data:

¿ 4-3
calculations/conclusion

I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: ____**

Week 9 Take-Home Quiz

Score:__________ /5

¿ THQ-1 (5-points)

Make your motor work for a non-physics person (parent, friend, English major, etc.) and have them sign the below affidavit confirming that they saw your motor working. However, you do <u>not</u> need to have the affidavit notarized.

Show a non-physics person that you can successfully build a working motor. Note: if someone is stuck, please get advice from another student!

"Yes, I have seen this student build a motor that successfully runs (on electrical input power). I am considering getting one myself."

Non-physics person signature:____

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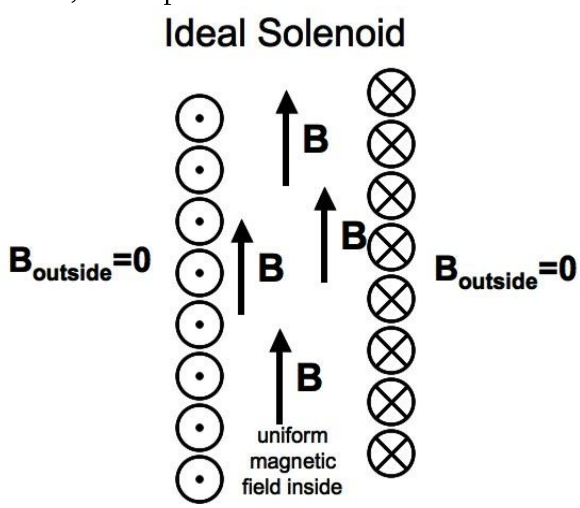
Week 10 Pre-Lab: Solenoids

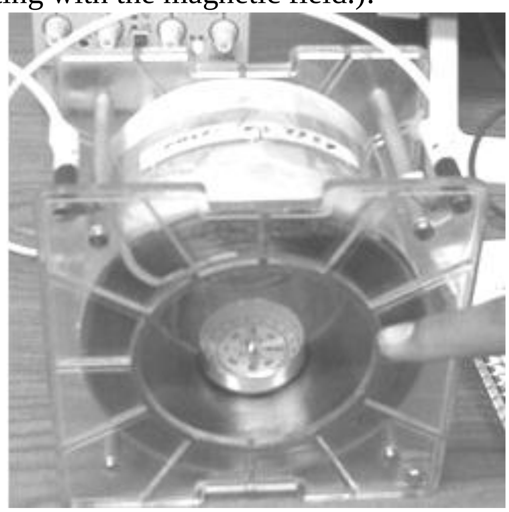
A current carrying wire creates a magnetic field around the wire. This magnetic field may be found using the Biot-Savart Law $d\vec{B} = \frac{\mu_o}{4\pi}\frac{I \cdot d\vec{s} \times \hat{r}}{r^2}$. However, this law can be difficult to use. If there is a high degree of symmetry, you may choose to find the magnetic field produced by the current carrying wire using Ampere's Law:

$$\oint_{\substack{\text{whole}\\\text{Amperian}\\\text{loop}}} \vec{B} \bullet d\vec{s} = \mu_o I_{\substack{\text{total enclosed by}\\\text{Amperian loop}}}.$$

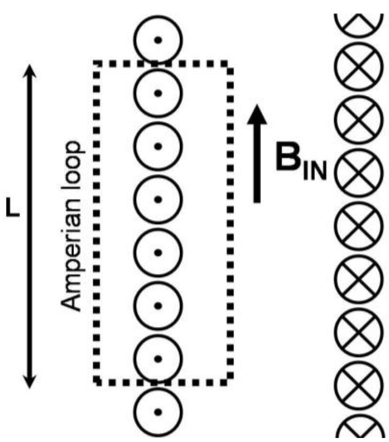
Ampere's Law simplifies finding a magnetic field in the same manner that Gauss's Law simplifies finding an electric field.

Examine the ideal solenoid (also called "inductor") where a very long coil of wire carries a current I is found to have a nearly uniform magnetic field inside the coils and a nearly zero magnetic field outside the coils. A cross sectional picture is provided (along with an actual solenoid, a compass inside its coils can be seen interacting with the magnetic field.):





In the laboratory, an experimenter may easily control the current through a solenoid, and so it is desirable to determine the strength of the magnetic field inside the solenoid as a function of the current. Because of the high degree of symmetry in the ideal solenoid, Ampere's Law may be used to find the magnetic field inside the solenoid.



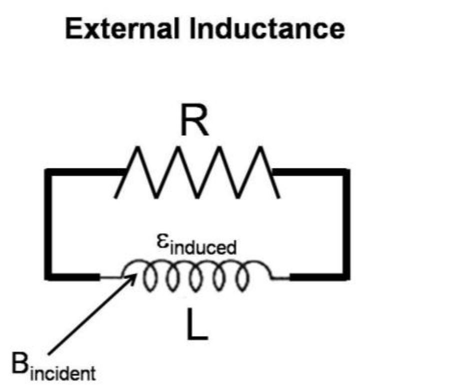
$$\text{LHS}: \oint_{\text{whole loop}} \vec{B} \bullet d\vec{s} = \int_{\substack{\text{inside}\\\text{solenoid}}} \vec{B} \bullet d\vec{s} = \int_0^L B_{\text{in}}\, dy = B_{\text{in}} \int_0^L dy = B_{\text{in}} L$$

$$\text{RHS}: \mu_o I_{\substack{\text{total}\\\text{enclosed}}} = \mu_o NI = \mu_o NI$$

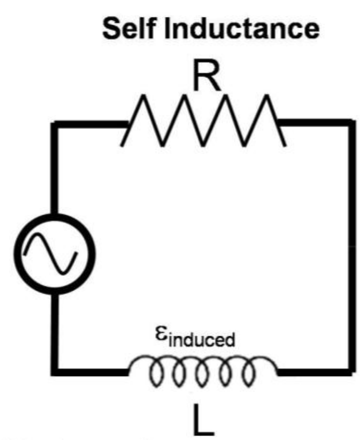
$$\text{LHS} = \text{RHS}: B_{\text{in}} = \frac{\mu_o NI}{L} = \mu_o nI$$

Two very important concepts in the study of electricity and magnetism are Ampere's Law and Faraday's Law. Ampere's Law states that a current in a wire creates a magnetic field. Faraday's Law states that if the magnetic field changes (oscillates) the changing magnetic field will create a voltage in the wire (with the strange choice of epsilon ε_L as the variable to represent this voltage): $\varepsilon_{\mathrm{L}}(t) = -\frac{d\phi_B}{dt}$, where ϕ_B is the magnetic flux, which has units of magnetic field times area. If a magnetic field is uniform over a certain area A, then the magnetic flux is easy to calculate $\phi_B = B \cdot A\ \left[\mathrm{T} \cdot \mathrm{m}^2\right]$. This voltage ε_L that is created by the changing magnetic field is call the "back EMF" or the "self-induced EMF". EMF stands for electromotive force, which seems a very bad convention since it is really a voltage and not a force (blame history)! The crucial point is that it is the rate of change of the magnetic flux that determines the amount of the voltage across the inductor (solenoid).

Faraday's law does not specify whether the magnetic field (flux) producing the voltage ε_L is from an external source or from the magnetic field that the solenoid itself has created.



An oscillating external B causes an induced voltage $\varepsilon_{induced}$ across the inductor.



Oscillating voltage source causes oscillating B inside inductor which induces a voltage $\varepsilon_{induced}$ across the inductor.

If the magnetic field is from an external source like a radio wave that happens to travel through the solenoid, then the induced voltage ε_L created across the solenoid could be used to detect the presence of the magnetic field. The induced voltage will act like a voltage source and cause a current that can be measured.

If the magnetic field is created by the solenoid itself, then the induced voltage ε_L created across the solenoid will oppose the voltage source of the circuit and the inductor will effectively act like a resistor (with some special features).

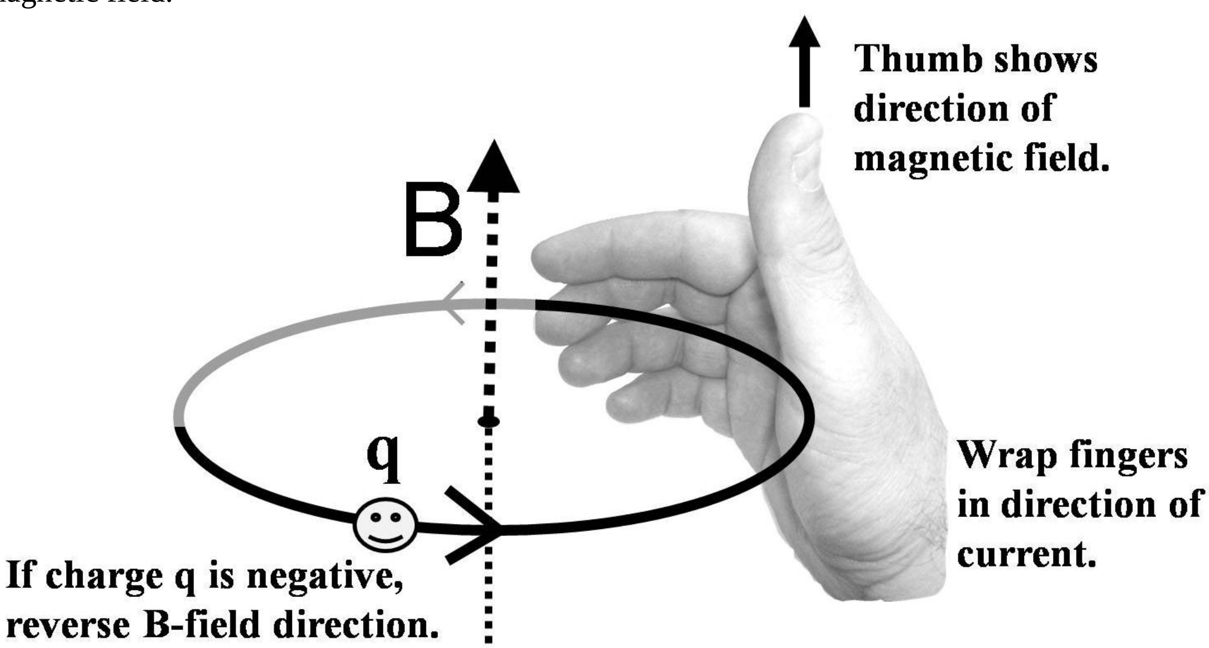
Week 10 Lab: Solenoids

Students Absolutely Must Learn…

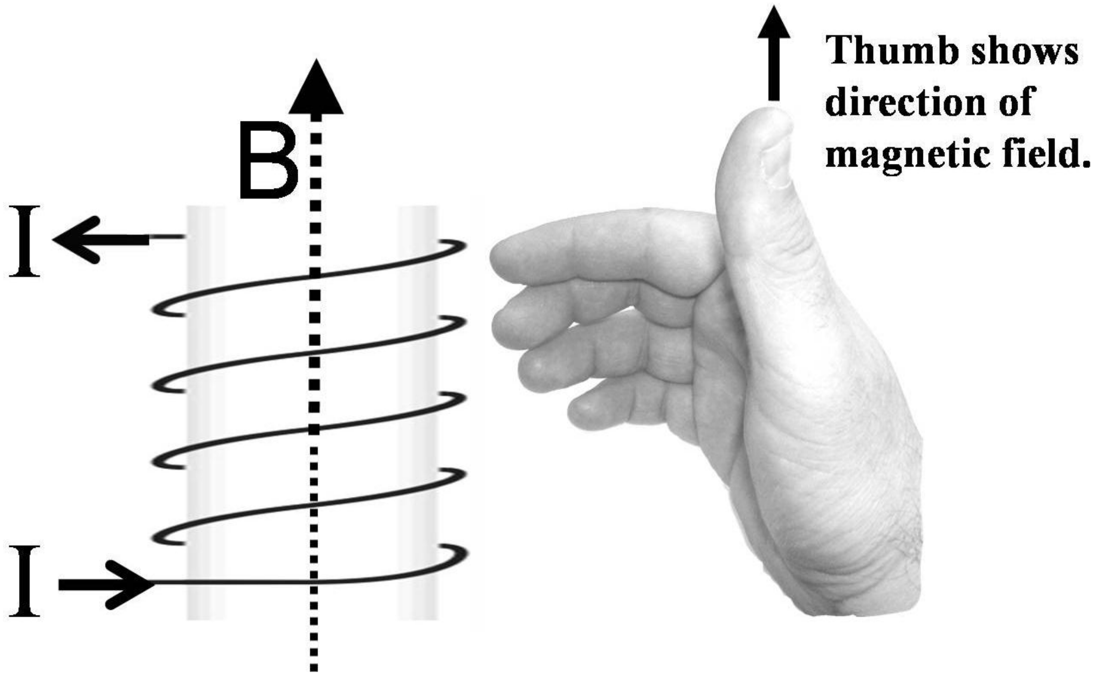
- How to use Ampere's law.
- Phase lag of inductors.
- How to use Faraday's law.
- How induction works: external, self and mutual.
- How to use Lenz's law.
- Advanced features of oscilloscopes.

Section 1: creating magnetic fields inside the solenoid

Magnetic fields are created by moving charges. A revolving charge produces a magnetic field parallel to the plane of its motion. The *right hand wrap rule* indicated the direction of that magnetic field.



When currents flow through coils of wire, many charges are moving simultaneously in circular paths. These create a magnetic field inside the wire coils. The *right hand wrap rule* again indicates the direction of this magnetic field.



Now you will experimentally examine the magnetic field produced by a solenoid with current flowing through it. Note that a real solenoid produces a magnetic field qualitatively similar to a bar magnet of the same dimensions.

First check that your compass has not been "flipped". The compass arrow should align itself with the local magnetic field produced by the Earth. Remember that the Earth's north magnetic pole is at the geographic south pole. This causes the local magnetic field to point toward the north geographic pole. The compass aligns with this magnetic field and thus points toward the north geographic pole. If your compass has been flipped, fix it with a strong magnet or tell your TA so they can fix it.

Examine the direction of the windings of your solenoid. You can tell which way the current circulates by how the wire enters the solenoid. Then you can use the right-handed screw rule to determine the direction of the magnetic field inside the solenoid (which side is north and which is south).

¿ 1-1

Even though the solenoid is made of wire (wound into a coil), it is so long that it actually has some sizeable resistance. Use a DMM to measure the resistance of the solenoid (so this is a real solenoid, not an ideal solenoid).

¿ 1-2

Apply <u>constant</u> current using the <u>constant voltage supply</u> (a few volts should be good) to your solenoid. Find the current in the solenoid using Ohm's law.

¿ 1-3

Use the right-handed screw rule to predict the positive direction (north pole) of the magnetic field produced within the solenoid and the magnetic field surrounding the solenoid in general. Test your prediction using the compass and sketch the magnetic field surrounding the solenoid below. Be sure to draw your solenoid in such a way as to show the reader how the current flows through the solenoid.

Next you will experimentally observe the process of self-inductance.

¿ 1-4

Place a solenoid in series with a 100 [Ω] resistor and drive this simple RL circuit with a sinusoidal source voltage with 10 [Hz] (very slow) and 5 [volts] source amplitude. Set your oscilloscope to measure the voltage across the resistor. Find how much current is flowing through the resistor and therefore the solenoid (the current *amplitude*).

¿ **1-5**

Qualitatively examine what happens to the current in the solenoid (by examining resistor voltage) as you increase the driving frequency from 100 [Hz] to higher frequencies. Your observations:

The impedance χ_L of an inductor is found to be $\chi_L = \omega_{\text{drive}} L$ where L is the self-inductance parameter of the solenoid and ω_{drive} is the angular driving frequency. The total circuit impedance without a capacitor is given by $Z = \sqrt{R^2 + \chi_L^2}$. The total circuit impedance Z has units of [ohms] for a reason; it acts as the total "resistance" of the circuit and thus can be combined with the source voltage to determine the circuit's current $I_{\text{amplitude}} = \frac{V_{\text{source,amplitude}}}{Z}$.

¿ **1-6**

Since $I_{\text{amplitude}} = \frac{V_{\text{source,amplitude}}}{Z}$, explain how the current would change if the angular driving frequency ω_{drive} was increased. (This is another way to think about question 1-5.)

¿ **1-7**

Now using the same circuit as the previous questions, set up your oscilloscope to measure the voltage of both the resistor and inductor using a middle ground configuration (with one channel inverted). Experimentally observe the 90^o phase shift that shows the oscillating inductor voltage leads the oscillating resistor voltage by $\pi/2$ (90^o). Make a quick sketch of your observations below, and check with students in other groups to see that you are getting things correct.

! **Warning: at very low frequencies, you will not see a phase shift between V_L and V_R (explained in the next passage).**

At very low frequencies, the self-induced back EMF goes to zero because dB/dt is nearly zero. You would then think that V_L=0 [V]. However, many inductors are made of such long amounts of wire that they have a sizeable resistance that makes the inductor act in part as a resistor. Two resistors in series will be in phase so that you will not measure any phase shift in this case (when the frequency it too low).

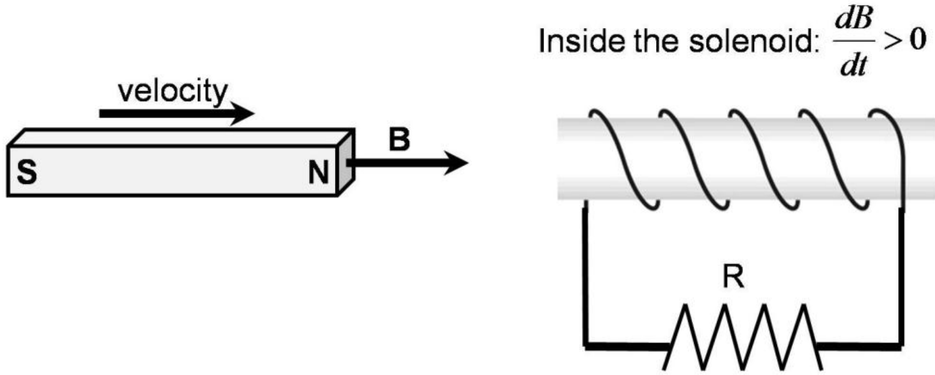
¿ **1-8**

Check for yourself that the solenoid acts as a pure resistor at very low frequencies . Below what frequency is it obvious that the phase shift between V_L and V_R is no longer $\pi/2$?

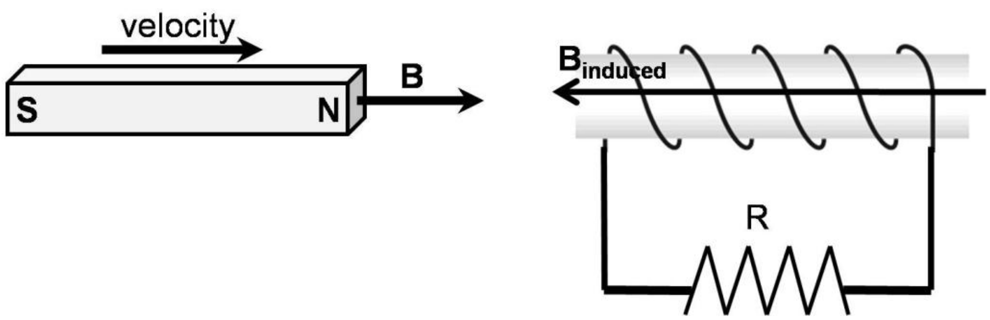
Section 2: Lenz's law

Restating previous ideas, Faraday’s Law states that a changing magnetic field will induce a voltage: $\varepsilon_L = -\frac{d\phi_B}{dt}$. Technically this equation shows that the induced voltage is proportional to the rate of change of the magnetic flux, but the magnetic flux is just the magnetic field integrated over the surface area of the circuit. In simple situations where the area is constant, this just becomes $\frac{d\phi_B}{dt} = \frac{d(A \cdot B)}{dt} = A\frac{dB}{dt}$. Since the presence of a induced voltage is effectively like adding a battery to a circuit, a current can be induced in a circuit without any other voltage source present!

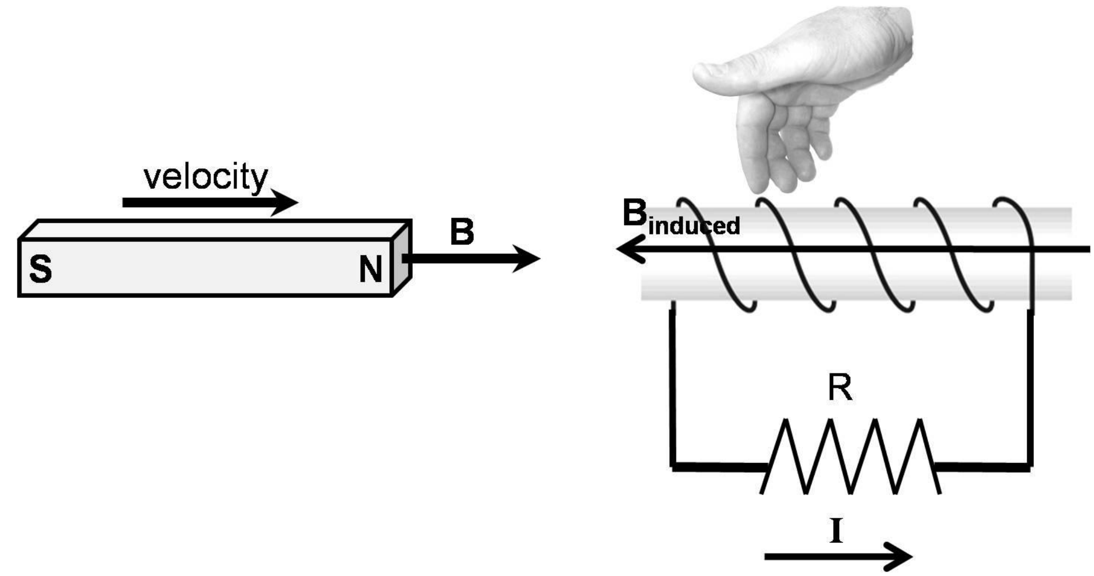
An interesting example of this is when a magnet approaches a solenoid in series with a resistor:



Here the magnet’s north pole is approaching the solenoid from the left. The magnetic field strength is growing inside the inductor coils as the magnet approaches $\frac{dB}{dt} > 0$. This causes current to flow in the coil which creates its own magnetic field.

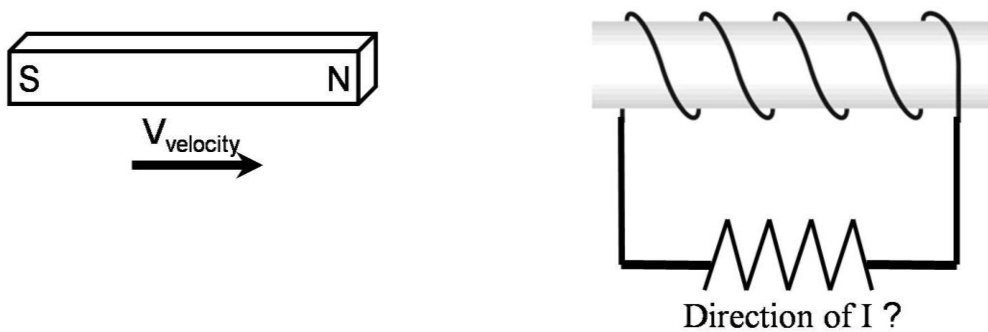


Lenz’s Law states that the induced magnetic field must cause the moving magnet to slow down. Think of this in terms of conservation of energy, we expect the resistor to absorb energy from the current in the solenoid. This energy has to come from somewhere; it comes from the kinetic energy of the moving magnet which must slow down to turn some of its own kinetic energy into the heating of the resistor. Once you figure out which direction the induced magnetic field must be to slow the moving magnet, you use the right hand rule to figure out the direction of the current in the solenoid coils.

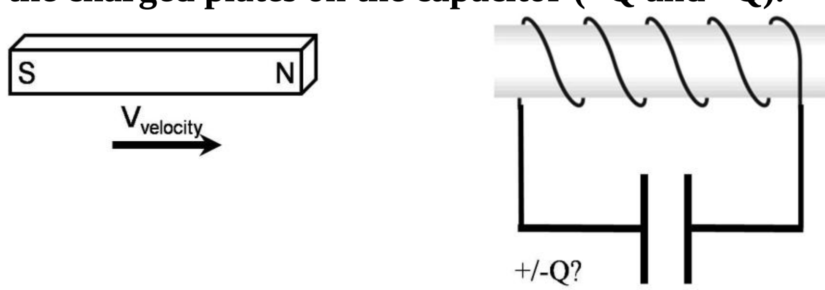


It is a little tricky to see, but if you follow how your fingers wrap around the coils, you find the direction of the current. (Ask other students or get your TA if you don't see why the current is flowing to the right in the previous picture.) Be careful, if the solenoid had been wound differently, the current direction would have been reversed (more practice examples are next to check your understanding).

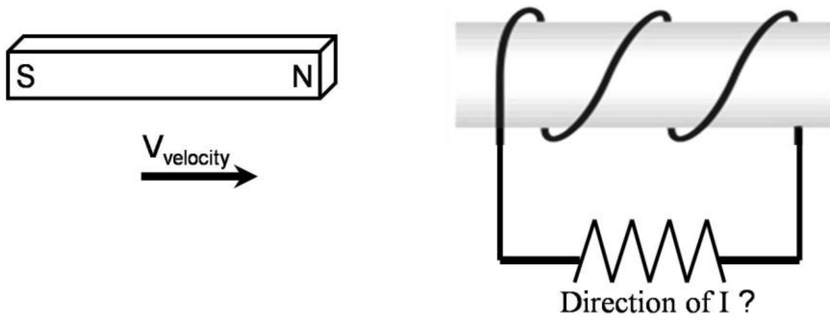
¿ 2-1 Draw the correct current direction in the resistor.



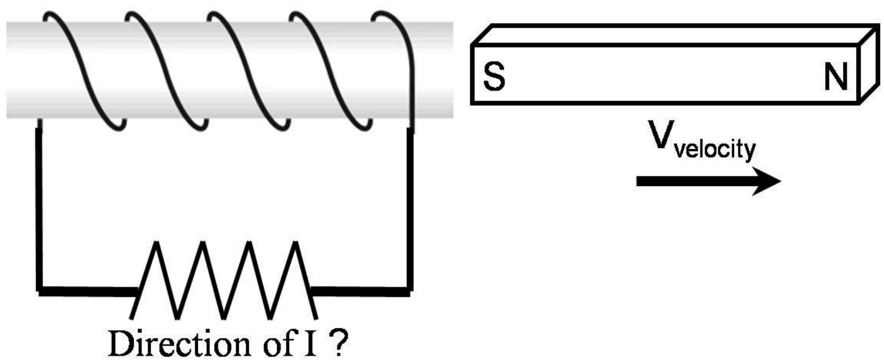
¿ 2-2 Draw the charged plates on the capacitor (+Q and –Q).



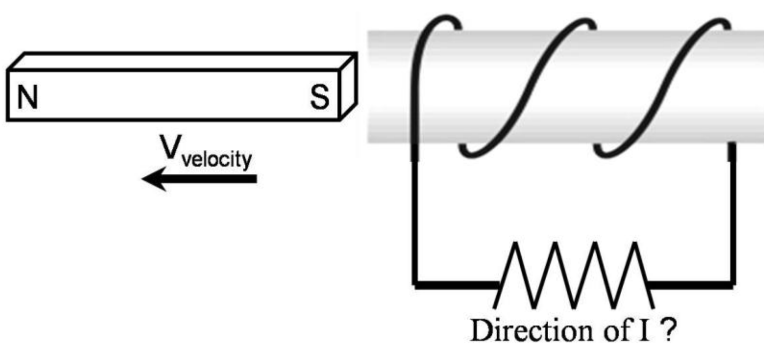
¿ **2-3 Draw the correct current direction in the resistor.**



¿ **2-4 Draw the correct current direction in the resistor.**



¿ **2-5 Draw the correct current direction in the resistor.**



¿ **2-6**

Explain why a strong magnet dropped down a copper pipe would fall much more slowly than you would naively expect?

Section 3: induced solenoid voltage by external magnetic fields

Now you will experimentally observe how a changing magnetic field induces a voltage in an unpowered solenoid. Check your bar magnet with your compass to see that it is labeled correctly. Remember that the compass's needle labeled "north" should point to south magnetic poles (like the north geographic pole of the earth).

Hook up your unpowered solenoid directly to the oscilloscope by itself so you can measure the electric potential difference between both ends. Don't bother placing a resistor in series. Instead you will just examine the direction of the back EMF by checking the sign of the voltage across the solenoid caused by the back EMF.

¿ 3-1

Move the north pole slowly toward one side of your solenoid. Write what you see on your oscilloscope (positive or negative induced voltage). You should see some induced voltage or you are moving too slowly. Try using 500 ms/div (1/2 second/division) and 50 mV/div to clearly see the response. Your observations:

¿ 3-2

Move the north pole quickly toward *same* side of your solenoid as in 3-1. Write what you see on your oscilloscope and compare the amplitude of the induced voltage with 3-1. Your observation and comparison:

¿ 3-3

Use the equation for Faraday's Law $\varepsilon_L = -\frac{d\phi_B}{dt}$ **to explain why the amplitude 3-2 was larger than 3-1.**

¿ 3-4

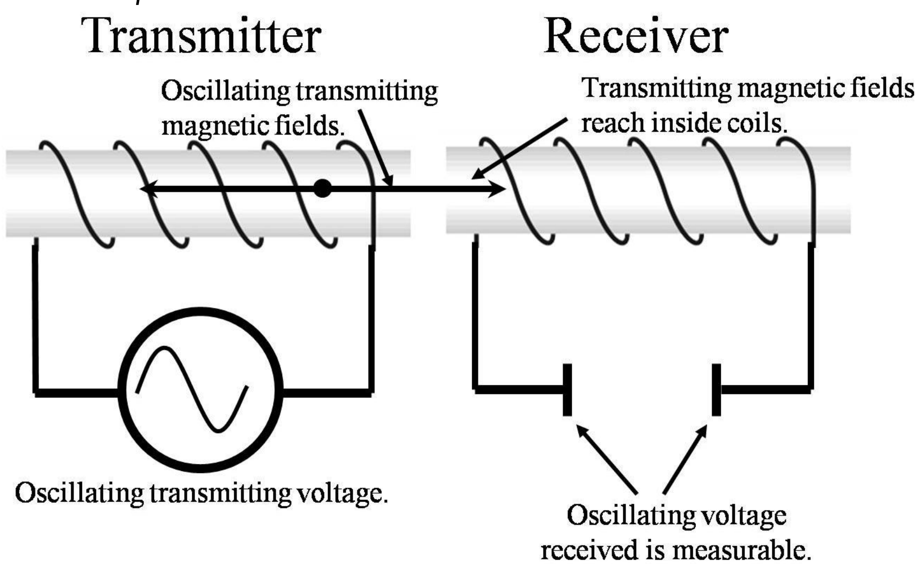
Now move the <u>south pole</u> quickly toward the *same* side of your solenoid as in 3-1 and 3-2. Write what you see on your oscilloscope and compare your result with that of 3-3. Your observation and comparison:

¿ 3-5

Use Lenz's Law to explain the difference between your observations in 3-3 and 3-4. Your explanation:

Section 4: finding the mutual inductance

If you take a solenoid and drive it with an alternating current, it will produce an alternating magnetic field inside its coils. If you then take another solenoid that is unpowered and place it nearby so that the changing magnetic field of the first solenoid reaches inside the coils of the second solenoid, then a voltage will be induced in the second solenoid *despite the fact that the wires of each solenoid in no way touch each other*. This is the process of **mutual inductance** and is the basis of *transformers* in transmission lines.



The definition of the **mutual-inductance** is:

$$M_{\substack{\text{transmitter}\\\text{to receiver}}} = \frac{\varepsilon_{\text{receiver, amplitude}}}{\left(\dfrac{\mathrm{dI}_{\text{transmitter}}}{\mathrm{dt}}\right)_{\text{amplitude}}}.$$

The mutual inductance parameter M can be used to encapsulate all the geometric information of the combined solenoids. It is used in engineering so that you can calculate the transmitted voltage from an applied current without having to calculate the magnetic field and geometric factors with a rearranged version $\varepsilon_{\text{receiver}} = -M_{\substack{\text{transmitter}\\\text{to receiver}}} \cdot \dfrac{\mathrm{dI}_{\text{transmitter}}}{\mathrm{dt}}$ measured in [henries] or [H]).

¿ 4-1

If you have two solenoids close together with M = 0.2 [H], and you drive one circuit with a current $I(t) = 6\sin(666t)\,[\mathrm{A}]$, find the amplitude of the induced voltage in the second solenoid.

The derivative of the sinusoidal current is

$$\left(\frac{dI_{\text{transmitter}}}{dt}\right)_{\text{amplitude}} = \frac{\omega_D}{R} V_{\substack{\text{resistor, transmitter} \\ \text{amplitude}}} .$$

Thus

$$M_{\substack{\text{transmitter} \\ \text{to receiver}}} = \frac{\varepsilon_{\text{receiver}} R}{-\omega_D V_{\substack{\text{resistor, transmitter} \\ \text{amplitude}}}}$$

This result can be used to experimentally determine the mutual inductance of combined solenoids.

Now you will experimentally study the process of mutual inductance. Use a function generator to drive a solenoid in series with a 10 [ohm] resistor. Use a sinusoidally oscillating source voltage of 5 [volts] amplitude. This solenoid is the *transmitter*. As the current oscillates in the solenoid's wire, an oscillating magnetic field is created inside the solenoid (due to Ampere's law).

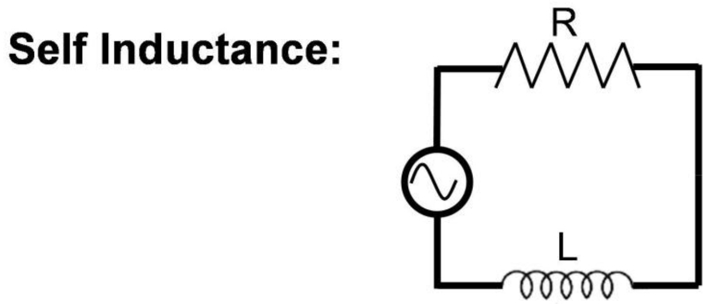
Hook up the other undriven solenoid directly to the oscilloscope. This solenoid is essentially the *receiver*. It will detect the presence of *changing* magnetic fields just as you saw in section 3.

Place the solenoids together as close as possible so that you can measure the maximum induced voltage amplitude in the receiver. Placing soft iron inside the coils can increase the magnetic field inside the solenoids so that transmission is increased (this is done in most transformers including the giant transformers in power lines).

¿ 4-1

Make the "single measurement" to experimentally determine the mutual inductance M of your two combined solenoids. {Record data and make calculations below.}

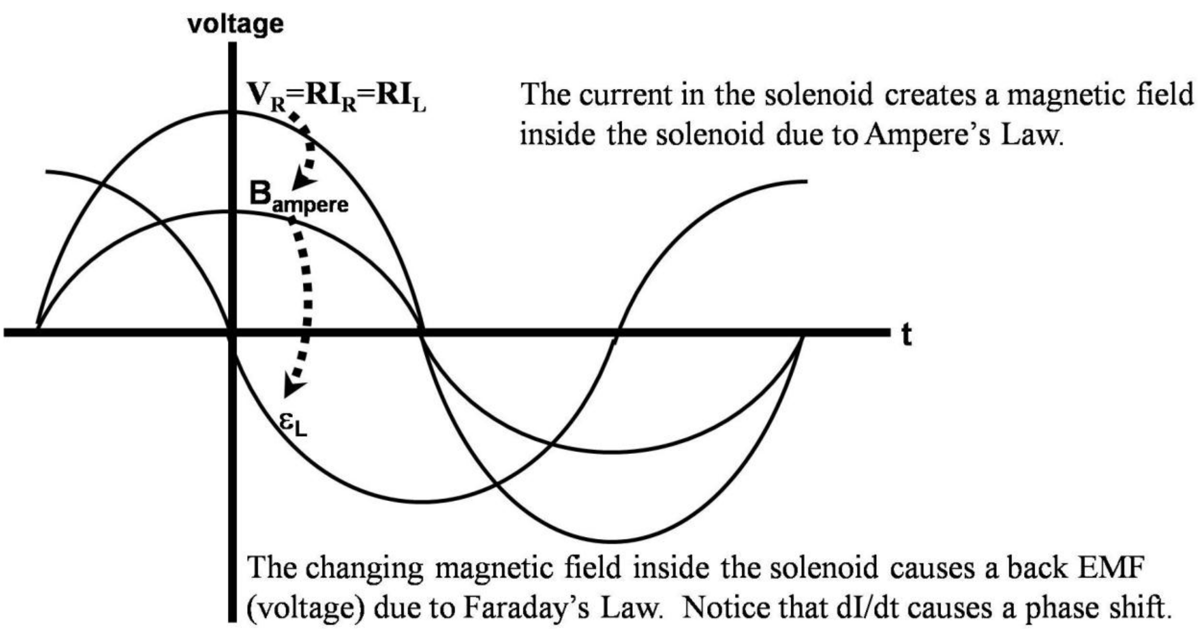
Section 5: finding the self-inductance



The logical flow of ideas is:

- The oscillating voltage source causes an oscillating current in the circuit (and solenoid).
- The oscillating current inside the solenoid wire causes an oscillating magnetic field inside the solenoid coils.
- The oscillating magnetic fields cause a changing back EMF across the solenoid.

This is shown graphically for an oscillating circuit with a resistor and inductor in series.



The above figure demonstrates the cause and effect relationships responsible for creating the voltage drop across a solenoid *even though it is just one long conducting wire!*

If you are examining an RL circuit driven by a sinusoidal voltage source, then you will obtain the following equations describing the voltages of the components. Notice the similarity to

$$V_{\text{source}}(t) = V_{\substack{\text{source}\\ \text{amplitude}}} \sin(\omega_{\text{D}} t + \phi)$$

$$V_{\text{R}}(t) = \left(\frac{R}{Z}\right) V_{\substack{\text{source}\\ \text{amplitude}}} \sin(\omega_{\text{D}} t)$$

$$V_{\text{L}}(t) = \left(\frac{\text{X}_L}{Z}\right) V_{\substack{\text{source}\\ \text{amplitude}}} \sin\left(\omega_{\text{D}} t + \frac{\pi}{2}\right)$$

Compare to the RC circuit that is sinusoidally driven:

$$V_{\text{C}}(t) = \left(\frac{\text{X}_C}{Z}\right) V_{\substack{\text{source}\\ \text{amplitude}}} \sin\left(\omega_{\text{D}} t - \frac{\pi}{2}\right).$$

Notice that like the capacitor voltage, the inductor voltage is phase shifted from the resistor voltage by $\pi/2$.

X_L is the inductive reactance of the solenoid and is given by $\text{X}_L = \omega_{\text{drive}} L$. Compare this to the capacitive reactance of the RC circuit: $\text{X}_C = \dfrac{1}{\omega_{\text{drive}} C}$. The inductive reactance of an RL circuit is directly proportional to the driving frequency. It is recommended that you use a 1,000 [Ω] resistor.

¿ 5-1

If you increase the driving frequency in a sinusoidally driven RL circuit, does the voltage you measure across the resistor increase or decrease? What about the inductor? Explain your reasoning.

When you measure $V_{R,\ amplitude} = \varepsilon_{L,\ amplitude}$, then you know that that $X_L = R$. If you find the frequency where this happens, you can use $X_L = \omega_{\text{drive}} L$ to find L by substituting R for X_L: $L = \dfrac{R}{\omega_{\text{drive}}}$.

¿ 5-2
Use this single measurement method to find L for your solenoid.

¿ 5-3
Use the XY setting of your oscilloscope to observe the 90^{o} phase shift between the resistor and inductor voltage by viewing the subsequent Lissajous figure.

There is a second multi-measurement method to find L. The voltage amplitudes of the sinusoidally driven RL circuit are very similar to those for the sinusoidally driven RC circuit you encountered a few weeks ago:

$$V(t)_{\text{resistor}} = \frac{R}{Z} V_{\substack{\text{source}\\ \text{amplitude}}} \sin(\omega_{\text{drive}} t)$$

and

$$V(t)_{\text{inductor}} = \frac{\mathrm{X}_L}{Z} V_{\substack{\text{source}\\ \text{amplitude}}} \sin\left(\omega_{\text{drive}} t + \frac{\pi}{2}\right).$$

This gives the following relationships for the amplitudes:

$$V_{\substack{\text{resistor}\\ \text{amplitude}}} = \frac{R}{Z} V_{\substack{\text{source}\\ \text{amplitude}}} \qquad \text{and} \qquad V_{\substack{\text{inductor}\\ \text{amplitude}}} = \frac{\mathrm{X}_L}{Z} V_{\substack{\text{source}\\ \text{amplitude}}}.$$

Dividing these two equations gives

$$\frac{V_{\substack{\text{inductor}\\ \text{amplitude}}}}{V_{\substack{\text{resistor}\\ \text{amplitude}}}} = \frac{\left(\dfrac{\mathrm{X}_L \cdot V_{\substack{\text{source}\\ \text{amplitude}}}}{Z}\right)}{\left(\dfrac{R \cdot V_{\substack{\text{source}\\ \text{amplitude}}}}{Z}\right)} = \frac{\mathrm{X}_L}{R}.$$

Therefore,

$$\mathrm{X}_L = R \frac{V_{\substack{\text{inductor}\\ \text{amplitude}}}}{V_{\substack{\text{resistor}\\ \text{amplitude}}}}.$$

In order to test the relationship $\chi_L = \omega_{\text{drive}} L$ and experimentally determine L for your solenoid, simply combine the last two equations:

$$\omega_{\text{drive}} L = R \frac{V_{\substack{\text{inductor}\\ \text{amplitude}}}}{V_{\substack{\text{resistor}\\ \text{amplitude}}}}.$$

Therefore if you graph

$$R\frac{V_{\substack{\text{inductor}\\\text{amplitude}}}}{V_{\substack{\text{resistor}\\\text{amplitude}}}}\ \text{vs. } \omega_{\text{drive}},$$

you should obtain a linear graph with a slope equal to L.

¿ 5-4

Find L by collecting data for multiple driving frequencies, making a graph on separate graph paper and finding the slope. Make your observations and graph now. Then write your work and result for L:

Section 6: fast Fourier transform (FFT) detection of frequencies

This is the perfect opportunity to learn the use of your oscilloscopes FFT (fast Fourier transfer) math function. The FFT math operation changes the time-axis to a frequency-axis. You may then adjust the frequency scale using the "seconds/div knob", zoom in using the "math > FFT zoom function", horizontally scan using the "horizontal shift knob".

A mathematical description of electromagnetic waves in the air is as follows:

$$A_{\substack{\text{waves}\\ \text{in air}}}(t) = A_1 \sin(\omega_1 t) + A_2 \sin(\omega_2 t) + A_3 \sin(\omega_3 t) + \ldots$$

An EM wave is made of many components of different frequencies. Each frequency has its own amplitude, A_1, A_2,… A Fourier transform is a mathematical technique that gives the amplitudes of the various components of wave. Your oscilloscope has this (fast) algorithm programmed into it!

¿ 6-1

Use your solenoid to search for stray alternating magnetic fields in the lab. There are many strange high-frequency electromagnetic oscillations (radio waves) permeating the laboratory. Use a large unpowered solenoid to detect the oscillating magnetic fields of these radio waves in order to measure the frequencies of these signals.

Section 7: authentic assessment

¿ 7-1

Transformers in power lines use metal contained inside their solenoid coils to help increase the mutual inductance. Investigate what kinds of metals and shapes thereof help increase the mutual inductance in a transformer. Use two large solenoids for this, the function generator and your oscilloscope. Various test metal pieces of different geometrical shapes are available in the lab: brass, stainless steel, galvanized steel, and aluminum. Take only one or two at a time and put them back immediately when you are done (i.e. share).

Sinusoidal electromagnetic waves (light) transmitted from one solenoid to another can be blocked by highly conducting objects. This is for the same reason that good conductors (metals) are shiny, they reflect light so it cannot pass. Investigate what kinds of metals are good or poor conductors using this effect. Use two large solenoids (with a gap between them) for this, the function generator and your oscilloscope. Metallic sheets are in one part of the room. Take only one or two at a time and put them back immediately when you are done.

Determine what shapes and metals placed inside solenoids maximize mutual inductance. Determine if stainless steel is a good or bad conductor.

If you are uncomfortable having another student check your work, please ask your TA.

"Yes, I have seen this student explore the effects of different materials and geometries on mutual inductance."

Student Signature:____

Section 8: open-ended

You wake as if in a dream. All is white, all is cold. It comes back slowly, the plans, the plane, the explosion. You were on an expedition to the Earth's polar region. But which one, north or south? You can't remember!

You find the debris field of the plane. Your oscilloscope, luckily in one piece, as well as your portable power supply. From the wrecked engine, you take a large solenoid. In your pocket (of course!), some wires and alligator clips. You rescue some cheap unlabeled ceramic magnets from the icy ground before they are covered by the falling snow and lost. A magnet could be used to make a compass *if only you knew which end was the north magnetic pole*! A compass is your only chance to figure out where on earth you are and then how to proceed!

Use your oscilloscope and solenoid (and wires) to devise a way to determine the north magnetic pole of an unlabeled magnet.

You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the following page.

¿ **8-1**
hypothesizing/planning:

¿ **8-2**
observations/data:

¿ **8-3**
calculations/conclusion

I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: ____**

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Week 10 Take-Home Quiz

Score:__________ /5

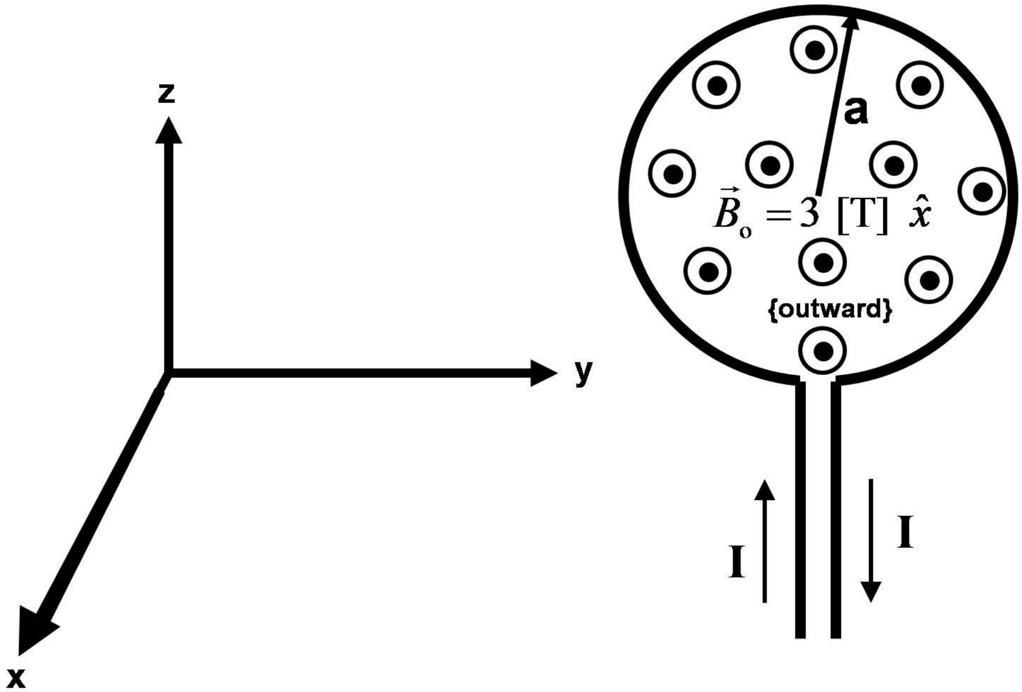
¿ THQ-1 (1-point)
Which law of physics indicates that a changing magnetic field may induce a voltage in a circuit?

¿ THQ-2 (1-point)
What mathematical operation allows one to decompose a wave into its frequency components?

¿ THQ-3 (1-point)
What fundamental physics principle justifies Lenz's Law?

¿ **THQ-4 (2-points)**

A single circular loop of wire of radius $a = 0.2$ [m] **encloses a sinusoidally oscillating, spatially uniform magnetic field** $\vec{B}_\text{o} = 3\cos(500t)$ [T] $\hat{x}$**. Use Faraday's law** $\varepsilon_\text{L}(t) = -\dfrac{d\phi_B}{dt}$ **to calculate the induced voltage across the wire loop as a function of time,** $\varepsilon_\text{L}(t)$**.**



Unit 6 Lab Report Instructions

Unit Lab Report [40 points]

Use the following section titles in your report. Images, text or equations plagiarized from the internet are not allowed! Remember to write your report *alone* as collaborating with a lab partner will make you both guilty of plagiarism. **Please label your lab report sections:**

- **Title [0 points]** – A catchy title worth zero points so make it unique and fun.
- **Mini-Report [10 points]:** ***{4-5 paragraphs, ~2 double-spaced pages}***
  Choose **one** of the following sections about which to write your mini-report:
  Week 11 Section 4 or Week 12 Section 3
  Write a "mini-report" for one particular section of the lab manual. Describe what you did succinctly, and then what you found accurately. Then explain what the result means and how it relates to some of the concepts in the previous section. *You must write using sentences & paragraphs; bulleted lists are unacceptable.* ***Please label your mini-report sections:***
  - **Abstract:** Write 2-3 sentences about the goals of this section. Describe the concepts you were investigating and how the experimentation you performed allowed you to investigate these concepts. Write 2-3 sentences summarizing the procedure. Write 2-3 sentences summarizing the results and what the results mean with regard to the concepts you were investigating. *It is best to write the abstract last*.
  - **Procedure:** Do not provide a lot of specific details, but rather you should summarize the procedure so that a student who took the course a few years ago would understand what you did.
  - **Results:** Provide a description of the data you obtained such as data tables. Restate any measured values, calculated slopes of lines-of-best-fit, etc. Do not *interpret* your results, save any interpretation for the discussion.
  - **Discussion:** Analyze and interpret the results you observed/measured in terms of some of the concepts and equations of this unit. It is all right to sound repetitive with other parts of the report.
- **Open-Ended Discussion [10 points]** – ***{1-2 paragraphs, ~1 page double-spaced}*** Choose **one** of the open-ended experiments from the two weekly activities to write about. Describe your experimental goal and the question you were trying to answer. Explain the ideas you came up with and what you tried. If your attempts were successful, explain your results. If your attempts resulted in failure, explain what went wrong and what you would do differently in the future. *You must write using sentences & paragraphs; bulleted lists are unacceptable.*
- **Graphs [5 points] - {attach to your typed report}** Graphs must be neatly hand-drawn <u>during lab</u> on graph paper. Your graphs must fill the entire page (requires planning ahead), include a descriptive title, labeled axes, numeric tic marks on the axes, and unit labels on the axes. If instructed to calculate the slope of the line-of-best-fit, write it directly on the graph.
  Week 11: none
  Week 12: 4-12
- **Take-Home Quizzes [2x5 points = 10 points] - {attach after your Graphs}**
- **Selected Worksheet Pages [5 points] - {attach after your Take-Home Quizzes }**
  Your TA will choose which pages you need to hand in.

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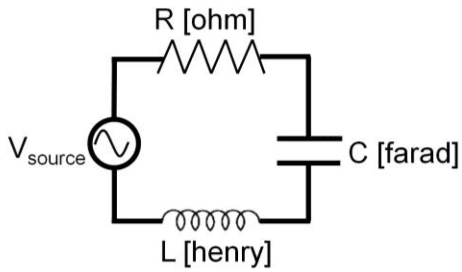
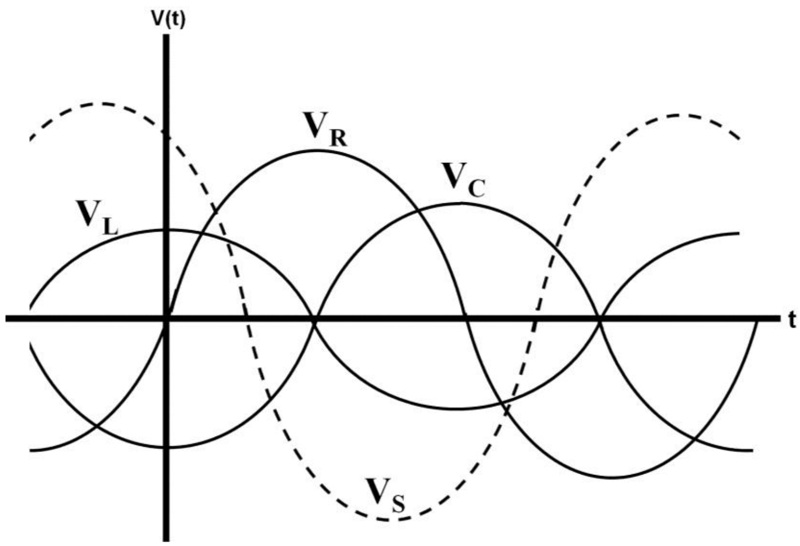
Week 11 Pre-Lab: RLC Circuit - AC Source



Just as the RC circuit with a sinusoidal source had sinusoidal voltages containing phase shifts, so too does the RLC circuit with sinusoidal source. You will need to understand the following (underived) time dependent formulae for RLC component voltages:

$$V(t)_{\text{source}} = V_{\substack{\text{source}\\\text{amplitude}}} \sin\left(\omega_{\text{drive}} t + \phi_{\text{shift}} + \pi\right) \qquad V(t)_{\text{resistor}} = \frac{R}{Z} V_{\substack{\text{source}\\\text{amplitude}}} \sin\left(\omega_{\text{drive}} t\right)$$

$$V(t)_{\text{capacitor}} = \frac{X_C}{Z} V_{\substack{\text{source}\\\text{amplitude}}} \sin\left(\omega_{\text{drive}} t - \frac{\pi}{2}\right) \qquad V(t)_{\text{inductor}} = \frac{X_L}{Z} V_{\substack{\text{inductor}\\\text{amplitude}}} \sin\left(\omega_{\text{drive}} t + \frac{\pi}{2}\right)$$



This graph shows that the resistor voltage has no phase shift as its graph goes through the origin. The capacitor voltage is phase shifted by π/2 from the resistor voltage while the inductor voltage is phase shifted by π/2 from the resistor voltage (in the opposite direction from the capacitor voltage). Finally, the source voltage is the negative sum of the other components $V_S(t) = -V_R(t) + -V_C(t) + -V_L(t)$ (due to conservation of energy). The phase shift of the source is more complicated depending on the parameters of the circuit: inductance L and capacitance C. This formula is provided later.

The voltage across each component oscillates at the same frequency as the driving frequency of the source, ω_{drive}. The properties of inductor and capacitor are frequency dependent, which makes the circuit respond differently to different driving frequencies. This causes there to be a specific frequency where the circuit has the largest possible current. This is the *resonant frequency*, ω_{resonant}.

The total circuit impedance (the circuit's total "resistance") is $Z=\sqrt{R^2+\left(X_L-X_C\right)^2}$ [Ω]. The capacitive reactance (the capacitor's "resistance") is time dependent, $X_C=\dfrac{1}{\omega_{\text{drive}}C}$ [Ω]. If you increase the driving frequency, X_C will decrease (inversely proportional). The inductive reactance (the inductor's "resistance") is time dependent also, $X_L=\omega_{\text{drive}}L$. If you increase the driving frequency, X_L will increase (linearly proportional). Since increasing the driving frequency causes X_C to decrease while X_L increases, then there is a specific driving frequency when they are equal, $X_C=X_L$. When this happens, the total circuit impedance is a minimum $Z_{\min}=\sqrt{R^2+\left(X_L-X_C\right)^2}=R$, and this particular driving frequency therefore allows the most current to flow through the circuit. This is called the *resonant frequency*.

The phase shift formula for the source voltage is $\phi_{\text{source}}=\tan^{-1}\left(\dfrac{X_L-X_C}{R}\right)$. Also, note that the familiar Ohm's law I=V/R can be used as a pneumonic for the formula for the current in the RLC circuit $I_{\substack{\text{current}\\\text{amplitude}}}=\dfrac{V_{\substack{\text{source}\\\text{amplitude}}}}{Z}$.

As an example, imagine an RLC circuits (sinusoidally driven) with the following parameters. If R = 0.5 [Ω], L = 0.010 [H], C = 0.10 [F], $V_{\text{source amplitude}}$ = 3 [V] and f_{drive} = 10 [Hz]. Then,

- $\omega_{\text{drive}}=2\pi f_{\text{drive}}=62\,[1/\text{s}]$
- $X_C=\dfrac{1}{\omega_{\text{drive}}C}=0.16\ [\Omega]$
- $X_L=\omega_{\text{drive}}L=0.62\ [\Omega]$
- $Z=\sqrt{R^2+\left(X_L-X_C\right)^2}=0.68\ [\Omega]$
- $\phi_{\text{source}}=\tan^{-1}\left(\dfrac{X_L-X_C}{R}\right)=0.74\ [\text{radians}]$
- $V(t)_{\text{source}}=V_{\substack{\text{source}\\\text{amplitude}}}\sin\left(\omega_{\text{drive}}t+\phi_{\text{shift}}+\pi\right)=3\sin\left(62t+0.74+\pi\right)$ [V]
- $V(t)_{\text{resistor}}=\dfrac{R}{Z}V_{\substack{\text{source}\\\text{amplitude}}}\sin\left(\omega_{\text{drive}}t\right)=2.2\sin\left(62t\right)$ [V]
- $V(t)_{\text{capacitor}}=\dfrac{X_C}{Z}V_{\substack{\text{source}\\\text{amplitude}}}\sin\left(\omega_{\text{drive}}t-\dfrac{\pi}{2}\right)=0.71\sin\left(62t-\dfrac{\pi}{2}\right)$ [V]
- $V(t)_{\text{inductor}}=\dfrac{X_L}{Z}V_{\substack{\text{inductor}\\\text{amplitude}}}\sin\left(\omega_{\text{drive}}t+\dfrac{\pi}{2}\right)=2.7\sin\left(62t+\dfrac{\pi}{2}\right)$ [V]
- $I_{\substack{\text{current}\\\text{amplitude}}}=\dfrac{V_{\substack{\text{source}\\\text{amplitude}}}}{Z}=4.4\ [\text{A}]$

Notice that at this driving frequency, of the three circuit components, the inductor has the largest voltage amplitude and would appear the largest on the oscilloscope screen.

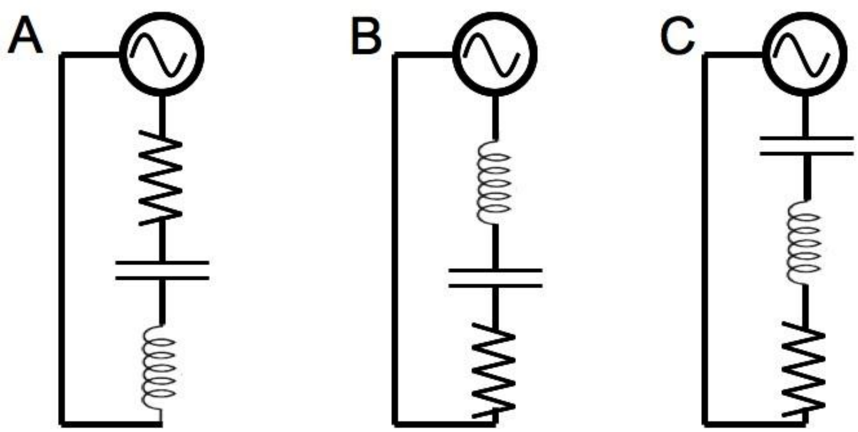
Week 11 Lab: RLC Circuit - AC Source

Students Absolutely Must Learn…

- How to use the sinusoidal solutions of the RLC circuit components and what they mean (including phase shifts).
- How to relate the RLC circuit current to other circuit parameters especially the circuit impedance.
- How conservation of energy and calculus explain the $\pi/2$ phase shifts.
- How to determine the resonance features of the RLC circuit and how the various parameters affect resonance.
- Advanced oscilloscope techniques.

Section 1: measuring with two oscilloscope channels

In electronics, you may use the oscilloscope to simultaneously measure the voltage of two *adjacent* components. Connecting your inductor, capacitor and resistor in series should be done with some consideration of which components you will measure with your oscilloscope since you only have two channels to measure with. The three circuit configuration examples below and the questions that follow are used to illustrate this point



¿ 1-1

In circuit A, which pairs of components can be separately measured on the oscilloscope with a middle ground technique? (*You are free to choose the location of the oscilloscope ground.*)

¿ 1-2

In circuit B, which pairs of components cannot be separately measured on the oscilloscope with a middle ground technique? (*You are free to choose the location of the oscilloscope ground.*)

¿ 1-3

In circuit C, which pairs of components can be separately measured on the oscilloscope with a middle ground technique? (*You are free to choose the location of the oscilloscope ground.*)

! Depending on which two components you wish to measure, you often have to rearrange the actual components.

¿ 1-4

Sketch a circuit configuration along with the proper placement of the three oscilloscope leads (red 1, red 2 and ground) in order to be able to separately measure the time dependence of the solenoid and resistor simultaneously.

¿ 1-5

Sketch a circuit configuration along with the proper placement of the three oscilloscope leads (red 1, red 2 and ground) in order to be able to separately measure the time dependence of the source and resistor simultaneously.

Section 2: calculus explains π/2 phase shifts

The explanation of the 90° phase shifts of the inductor and capacitor voltages from the resistor voltage can be explained using calculus.

Conservation of energy for the sinusoidally driven RLC circuit gives:

$$V_{\text{source}}(t)+V_{\text{L}}(t)+V_{\text{R}}(t)+V_{\text{C}}(t)=0.$$

Substituting Ohm's Law $V_{\text{R}}(t)=I(t)\cdot R$, the definition of inductance $V_{\text{L}}(t)=L\frac{dI(t)}{dt}$ and the definition of capacitance $V_{\text{C}}(t)=\frac{Q(t)}{C}$ gives:

$$V_{\text{source}}(t)+\underbrace{L\frac{dI(t)}{dt}}_{\text{inductor term}}+\underbrace{R\cdot I(t)}_{\text{resistor term}}+\underbrace{\frac{Q(t)}{C}}_{\text{capacitor term}}=0.$$

First notice that the time dependence of the inductor is related to the resistor by a time derivative,

$$V_{\text{source}}(t)+\underbrace{L\frac{dI(t)}{dt}+R\cdot I(t)}_{\substack{\text{The inductor voltage is}\\ \text{proportional to the time}\\ \text{derivative of the resistor voltage.}}}+\frac{Q(t)}{C}=0.$$

All time dependent quantities of the circuit are oscillating sinusoidally including $Q(t)$ and $I(t)$. Since the resistor voltage is described by a sine function, $V(t)_{\text{resistor}}=V_{\substack{\text{resistor}\\ \text{amplitude}}}\sin(\omega_{\text{drive}}t)$, the current is as well, $I(t)=I_{\text{amp}}\sin(\omega_{\text{drive}}t)$. Since

$$V_{\text{L}}(t)=L\frac{dI(t)}{dt}=L\cdot\omega_{\text{drive}}\cdot I_{\text{amp}}\cos(\omega_{\text{drive}}t),$$

so the inductor voltage must be described by a cosine function. But the cosine function is shifted from the sine function by π/2,

$$L\cdot\omega_{\text{drive}}\cdot I_{\text{amp}}\cos(\omega_{\text{drive}}t)=L\cdot\omega_{\text{drive}}\cdot I_{\text{amp}}\sin\left(\omega_{\text{drive}}t+\frac{\pi}{2}\right).$$

Thus calculus has explained the 90° phase shift of the inductor voltage relative to the resistor voltage.

Next remember the definition of current $I(t)=\frac{dQ(t)}{dt}$ to find that

$$V_{\text{source}}(t)+\underbrace{L\frac{dI(t)}{dt}}_{\text{inductor term}}+\underbrace{R\frac{dQ(t)}{dt}}_{\text{resistor term}}+\underbrace{\frac{Q(t)}{C}}_{\text{capacitor term}}=0.$$

Notice that the second two terms on the right hand side show that the time dependence of the capacitor voltage is related to the antiderivative of the resistor voltage,

$$V_{\text{source}}(t) + L\frac{dI(t)}{dt} + \underbrace{R\frac{dQ(t)}{dt} + \frac{Q(t)}{C}}_{\substack{\text{The capacitor voltage is}\\ \text{proportional to the antiderivative}\\ \text{of the resistor voltage.}}} = 0$$

Since the resistor voltage is described by a sine function, $V(t)_{\text{resistor}} = V_{\substack{\text{resistor}\\ \text{amplitude}}} \sin(\omega_{\text{drive}} t)$, the capacitor voltage must be described by a **negative** cosine function, the antiderivative of the sin function. But the negative cosine function is also phase shifted from the sine function by π/2,

$$-\cos(\omega_{\text{drive}} t) = \sin\left(\omega_{\text{drive}} t - \frac{\pi}{2}\right).$$

¿ **2-1**

Use the fact that $\frac{dI(t)}{dt} = \frac{d^2Q(t)}{dt^2}$ and use calculus explain in a different way why the inductor voltage is phase shifted from the resistor voltage by π/2. Begin with

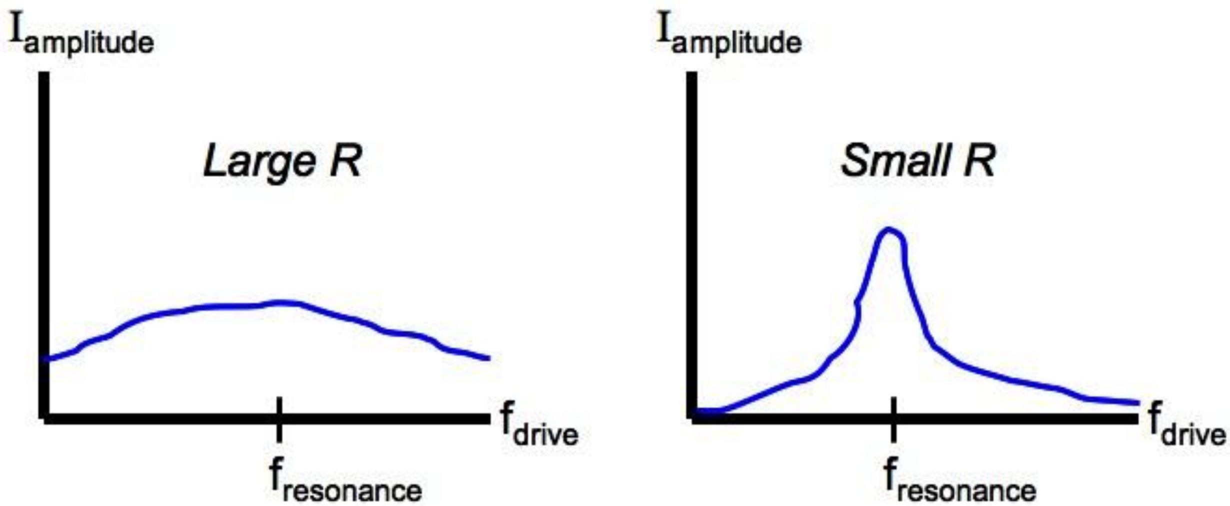
$V_{\text{source}}(t) + \underbrace{L\frac{d^2Q(t)}{dt^2} + R\cdot\frac{dQ(t)}{dt}} + \frac{Q(t)}{C} = 0$ **and** $Q(t) = -Q_{\text{amp}}\cos(\omega_{\text{drive}} t)$**.**

¿ **2-2**

Use calculus to explain why the capacitor voltage is phase shifted from the inductor voltages by π.

Section 3: extra lab techniques

An RLC circuit has a resonant driving frequency $f_{\text{resonance}}$ that maximizes the circuit current amplitude. Therefore, a plot of the current amplitude vs. driving frequency will show peak current amplitude at the resonant driving frequency. However, this graph can appear different depending on whether a large or small resistance is used in the circuit:



The sharpness of the resonance peak is measure by the quality factor Q. The larger the quality factor, the sharper the peak. Q is found to be given as

$$Q = \frac{\omega_{\text{resonance}} \cdot L}{\text{R}}.$$

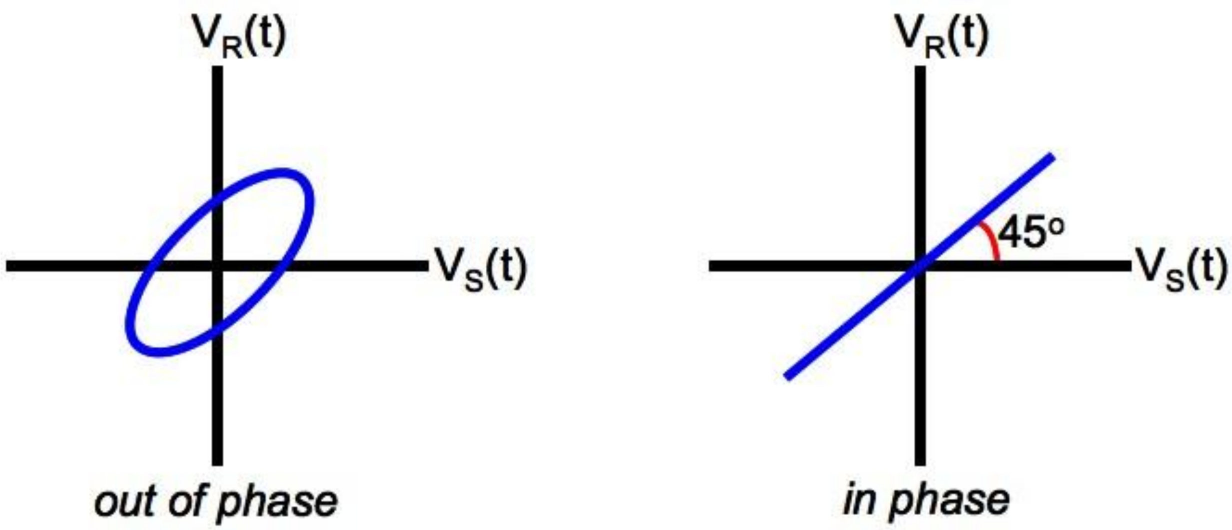
¿ **3-1**
What are the units of *Q*?

¿ **3-2**
Say you were building a circuit that needed to operate at many possible driving frequencies, and you wanted to avoid shorting out the components with a large current. Should you use a larger or smaller resistance?

¿ **3-3**
Say you were building a circuit that needed to operate at one specific frequency (near resonance), and you wanted to maximize the current through the circuit to do some work. Should you use a larger or smaller resistance?

In today's lab you usually want to use as small of a resistance as possible (while still being safe) in order to obtain a nice sharp peak in the current amplitude. This will make it easier to find the resonance frequency. However, it is not always desirable to have a large quality factor. In some mechanical systems (bridges, buildings, etc.) a pronounced response to a driving frequency can cause destruction.

The most accurate way to find $f_{\text{resonance}}$ is to utilize the fact that at resonance, $V_R(t)$ and $V_{\text{source}}(t)$ are exactly in phase with each other with equal amplitudes. You should place each of these voltages on your oscilloscope channels and examine an XY formatted display. The resonance frequency is easily found because you will see an ellipse when $V_R(t)$ and $V_{\text{source}}(t)$ are out of phase and a diagonal line when they are in phase. You see a straight line when they are in phase because both voltages must reach zero simultaneously.



Note that if R is chosen small enough, the resistance of the very long wire of the solenoid may become an appreciable resistance of the circuit. When this occurs, the amplitude of the resistor voltage will be smaller than the source voltage amplitude so that you will see a different angle of tilt (not 45°) of the in phase resonance line shown above. This is because

$$V_{\text{source}} + V_{\text{R}} + V_{\substack{\text{resistance of} \\ \text{real solenoid}}} + V_{\text{L}} + V_{\text{C}} = 0.$$

Section 4: specific oscilloscope measurements

Construct an RLC circuit driven by a sinusoidal driving voltage of $V_{\substack{\text{source}\\\text{amplitude}}} = 5$ [V] with $f_{\text{drive}} = 10{,}000$ [Hz], $R = 1$ [kΩ] , $C = 0.1$ [μF], and $L = 50$ [mH]. The frequency and resistance values were not randomly selected, but were determined so that R, χ_C and χ_L are of the same order of magnitude (check if you like). This means that $V_{\text{R,amp}}$, $V_{\text{C,amp}}$ and $V_{\text{L,amp}}$ will also be of the same order of magnitude. This "cheat" is only for this, your first time so you learn the measurement techniques better. Later you will need to be able to analyze two components on your oscilloscope when their voltages are drastically different.

¿ 4-1

Why must you hook up the entire circuit before setting the source voltage on the function generator? Why not just hook the function generator directly to the oscilloscope and set its properties first?

! You must keep this driving frequency the same as you are answering different questions (until told otherwise) because the properties of the circuit change with driving frequency.

¿ 4-2

It is often the case that components in a circuit become disconnected at bad solder joints even though you cannot see this with the unaided eye. What can you do experimentally to make sure that your RLC circuit is still conducting current through all its connections *without disconnecting the circuit*? {Hint: what information can the ohmic component give you?}

¿ 4-3

Quickly measure the voltage amplitudes of each component separately using a single channel of your oscilloscope. Double check that your source voltage amplitude is 5 [V] first.

¿ 4-4

Now use two-channel observations to simultaneously measure the resistor voltage and the inductor voltage to determine their respective phase shift. Don't forget that one channel should be inverted when using a middle ground configuration.

¿ 4-5

Now use two-channel observations to simultaneously measure the resistor voltage and the capacitor voltage to determine their respective phase shift.

¿ 4-6

Now use two-channel observations to simultaneously measure the inductor voltage and the capacitor voltage to determine their respective phase shift.

¿ 4-7

Now use two-channel observations to simultaneously measure the resistor voltage and the source voltage to determine their respective phase shift in seconds.

¿ 4-8

<u>Theoretical calculations</u>: Use the labeled values for inductance, capacitance and resistance that you have in your circuit as well as your actual driving frequency to calculate the following RLC circuit parameters in SI units.

χ_C

χ_L

Z

$\omega_{resonance}$

$f_{resonance}$

¿ 4-9

<u>Comparing theory and observation</u>: Use your results from the previous question along with your observed source voltage amplitude (should still be 5 [V]) to theoretically calculate the voltage amplitudes of the resistor, inductor and capacitor in SI units. Then compare each of these theoretically computed amplitudes to your previous observations.

Power: Since $$P_{\text{resistor}} = I \cdot V_{\text{resistor}} = \frac{(V_{\text{resistor}})^2}{R},$$

the power converted to heat by the resistor oscillates in time as a squared sine function:

$$P_{\text{R}}(t) = \frac{V_{\text{R}}^2(t)}{R} = \frac{V_{\text{R, amp}}^2}{R}\sin^2(\omega_{\text{drive}}t).$$

The average value of a squared sine function over a complete oscillation cycle is 0.5:

$$average\left[(\sin(\omega_{\text{drive}}t))^2\right] = \frac{1}{2}.$$

This means that the power consumed by the resistor averaged over time is

$$P_{\text{R, average}} = \frac{V_{\text{R, amplitude}}^2}{2R}.$$

¿ 4-10

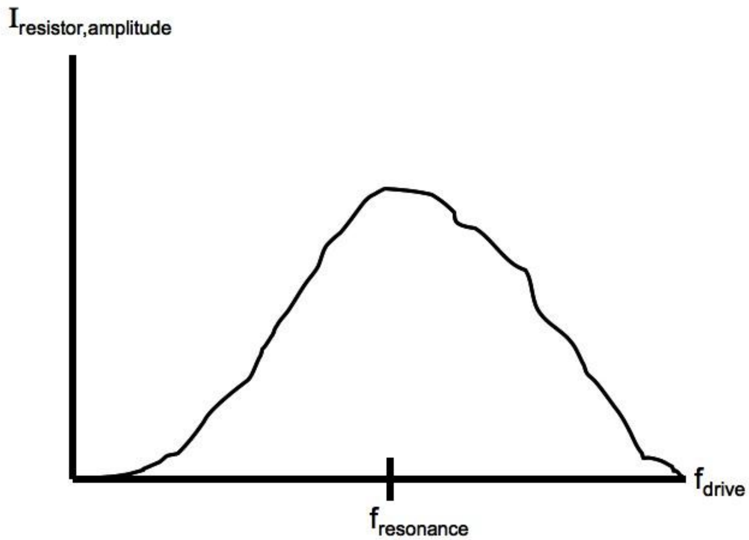
Use this formula to find the average power loss of your circuit in SI units.

¿ 4-11

When the driving frequency is at resonance, the voltages of the source and resistor are equal and in phase. Use this fact to search the range of driving frequencies for the resonant driving frequency using the technique described in section 4 of this lab. Compare this observed value to your predicted value.

¿ 4-12

Collect data of $I_{\text{amplitude}}$ vs. f_{drive} and record below. Then graph the data on separate graph paper. A slightly incorrect example (on purpose so you can't just copy) with a larger resistance is shown to help guide you.



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Section 5: authentic assessment

One solenoid and each of the four capacitors on the capacitor board allows you to construct four unique RLC circuits (not counting the resistance possibilities). You need to find the four resonant frequencies of each of these RLC circuits using the method described in section 4 on the phase relationship between the resistor and source voltages. Use the same solenoid as a different group so that you can compare answers.

! The inductor and capacitor voltage amplitudes can be larger than the source voltage amplitude. Voltages over 20 [V] can cause nasty shocks, and very large currents can be generated near resonance in circuits with a large quality factor Q. You should approach any circuit with care, not touching the components while the circuit is powered. In designing a circuit, one must either use a large resistance to limit the dangerous currents near resonance, or have a firm theoretical understanding of the maximum currents that the circuit can produce, while still proceeding with caution.

If you are uncomfortable having another student check your work, please ask your TA.

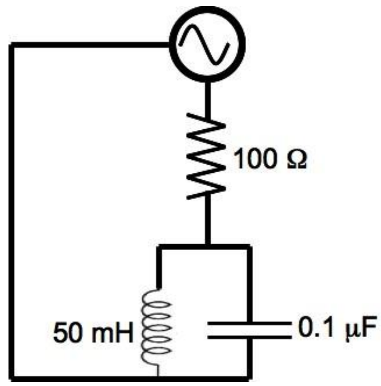
¿ 5-1

Show a student in a different group that you can successfully measure the resonance frequency of an RLC circuit (four circuits, compare your data with theirs). Once you are successful, have them sign below. Note: if someone is stuck, please give them advice!

"Yes, I have seen this student successfully find the resonance frequencies of four RLC circuits. Their results match mine. Either they are doing it right or we are both wrong in the same way!"

Student
Signature:____

Section 6: open-ended



Pretend that you are an old-timey inventor. You have already discovered the coiled wire device (now called inductor) and the metallic parallel plates device (now called capacitor). Resistors were discovered by a competitor of yours. It is still a sore subject around the workshop.

You have begun to combine these new components together in order to observe their compound behavior. You already found that when the inductor and capacitor are combined in series and driven sinusoidally, the circuit produces a special resonant frequency where the current in the circuit is a maximum. This means that civilization can now make electronics that “select” specific driving frequencies and “suppress” frequencies far from resonance.

Now you try combining the inductor and capacitor *in parallel* and drive them sinusoidally (see above figure). What electrical possibilities might this new compound device hold for the future of mankind? Well, use your anachronistic oscilloscope to find out. Try to deduce why this circuit may be said to have an “**anti**resonant frequency”, a different kind of effect on the circuit current.

You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the next page.

¿ 6-1
hypothesizing/planning:

¿ 6-2
observations/data:

¿ 6-3
calculations/conclusion

I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: ____**

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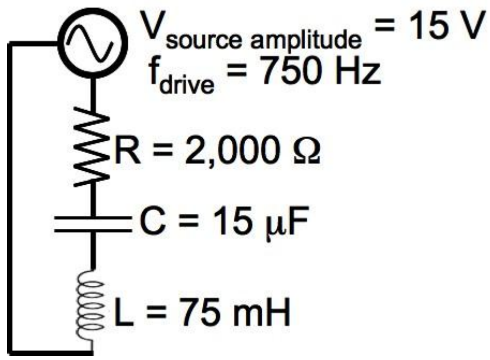
Week 11 Take-Home Quiz

Score:__________ /5

¿ THQ-1 (2-point)

Practice the math for an example of a sinusoidally driven series RLC circuit.



Calculate each of the basic RLC circuit parameters in SI units though not necessarily in the order given (SI units):

χ_C

χ_L

Z

$V_{\mathrm{R,amplitude}}$

$V_{\mathrm{C,amplitude}}$

$V_{\mathrm{L,amplitude}}$

ϕ_{source}

$I_{\mathrm{amplitude}}$

¿ THQ-2 (2-point)

Next write a time dependent equation for each quantity below using the numerical results from the previous question.

$V_{\text{source}}(t)$

$V_{\text{R}}(t)$

$V_{\text{C}}(t)$

$V_{\text{L}}(t)$

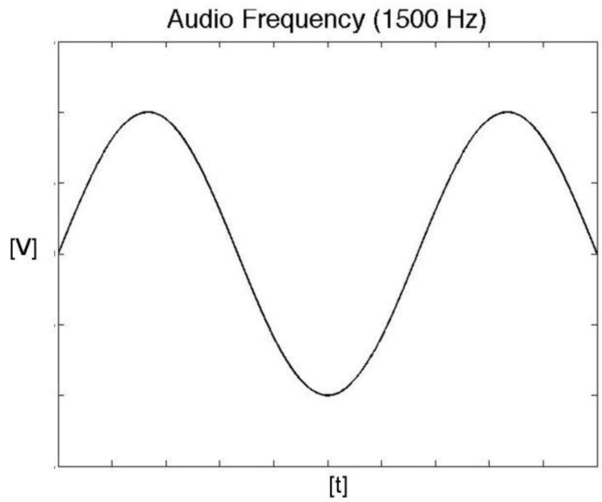
$I(t)$

$Q_{\text{cap}}(t)$

¿ THQ-3 (1-point)

What is the resonant driving frequency f_{resonant} of this circuit?

Week 12 Pre-Lab: RLC Radios



Modulating High Frequency Waves with Low Frequency Waves:

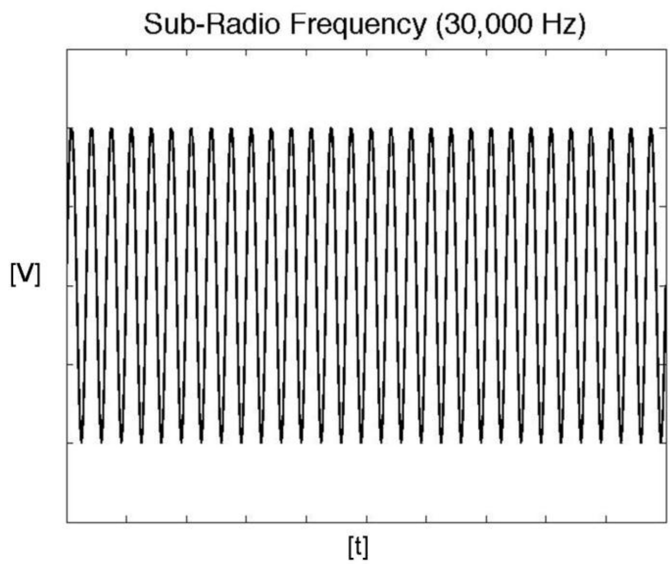
Imagine that you want to transmit a 1,500 [Hz] sound wave from one place to another. Clearly you could *play* the sound and have its vibrations be carried in the air as compression/rarefaction waves. But for long distance transport, you may want to turn the 'sound' into an electronic signal which can be transported with less energy loss along a wire. But if we need to transport the sound to many people (radio) or someone at a changing location (walkie-talkie), we can take advantage of our knowledge of electromagnetism and turn the sound wave into an electromagnetic wave and send the electromagnetic wave through the air. Of course an electromagnetic wave traveling through the air moves at the speed of light because an electromagnetic wave *is* light. We can turn our sound wave into light to transport it.

First investigate transporting sound as oscillating magnetic fields in solenoids, from one solenoid (the transmitter) to another solenoid (the receiver). The two solenoids are not connected in any way so that the oscillating magnetic field inside one solenoid must be made to oscillate within the other solenoid to utilize Faraday's Law of inductance, $\varepsilon_{\mathrm{L}} = -\frac{d\Phi_{\mathrm{B}}}{\mathrm{dt}}$, a process called mutual inductance.

Unfortunately, this wave is alternating much too slowly to induce a large voltage in the receiving solenoid. Remember the equation for mutual inductance, $V_{\substack{\text{induced}\\ \text{in circuit 2}}} = -\frac{\mathrm{dI}_{\text{circuit 1}}}{\mathrm{dt}} M_{1\text{ to }2}$, where M is a constant that describes how much the solenoids overlap. If the current doesn't oscillate rapidly enough, then $V_{\substack{\text{induced}\\ \text{in circuit 2}}}$ is very small.

You might say, "gee, I wish this wave oscillated more quickly to cause a bigger induced voltage in the receiving solenoid." But then it wouldn't be the same sound pitch that you wanted to hear in the first place! Still, it sounds like something you might say since you understand that to utilize Faraday's law, you need rapidly changing magnetic fields.

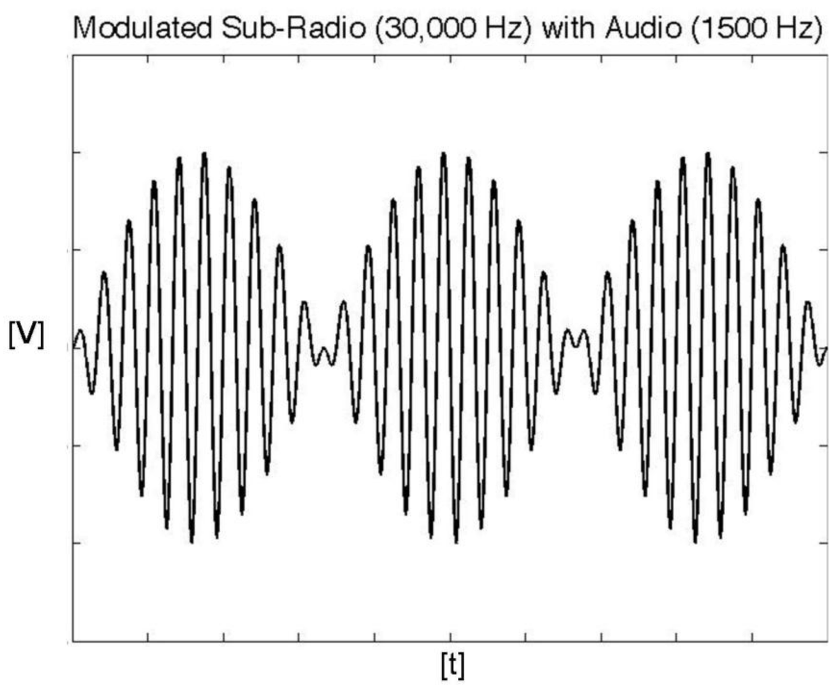
Next examine a wave that oscillates quickly at radio wave frequency or slightly sub-radio frequency.



This isn’t the frequency you want to hear (you are not able to!), but it does oscillate so quickly as to create a large induced voltage in the receiving solenoid. I.e., it oscillates quickly enough to be transmitted into the receiving circuit through the mutual inductance of the “transformer” (overlapping solenoids).

So what to do? There is a low frequency wave that carries the information we wish to transmit but can't, and there is a high frequency wave that we don't care about that is easily transmitted.

The solution is to ***combine*** the two waves together by ***multiplying*** them. This *modulated* wave has the properties of both waves: it carries information about the audio frequency component *and* it oscillates quickly enough to generate a highly induced voltage in the receiver circuit. The following picture shows what a modulated wave looks like.



The *envelope wave* is the low frequency oscillation while the high frequency oscillation is called the *carrier wave*. Together they are the *modulated wave*.

Week 12 Lab: RLC Radios

Students Absolutely Must Learn…

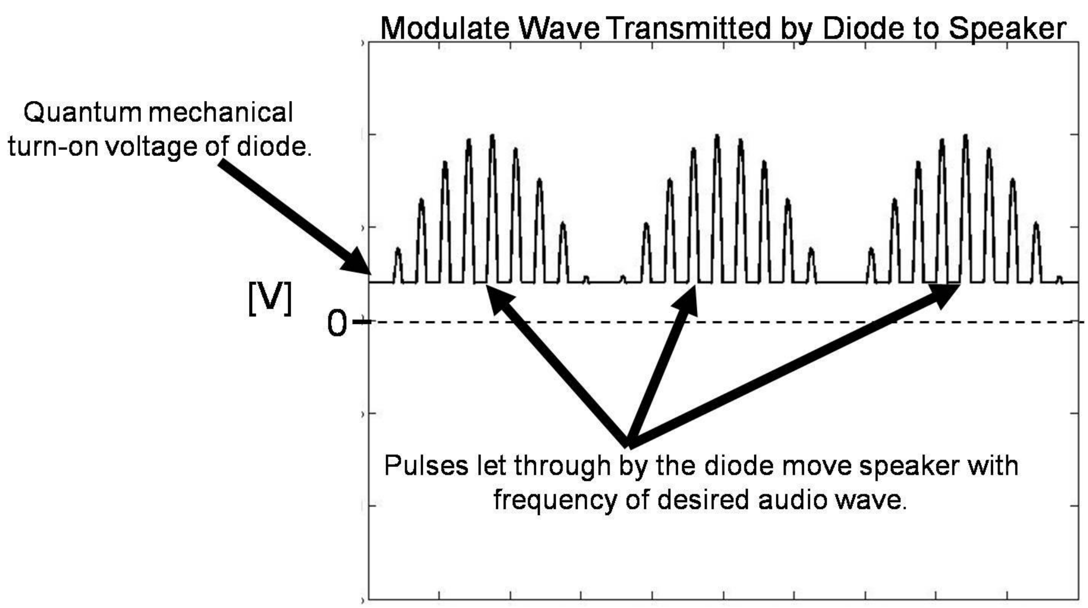
- How the RLC circuit's resonance may be used in technology.
- How to modulate a carrier wave and envelope.
- Advanced oscilloscope techniques.

Section 1: introducing the equipment

In today's lab, we would like to transmit a modulated sound wave transmitted by one solenoid into another "receiving" solenoid. We will use a capacitor in the second "receiving" circuit to make an RLC "receiving" circuit. By changing the capacitor of the "receiving" circuit, we can adjust its resonant frequency. Therefore, we will be able to "tune" our "receiver" to a particular radio frequency.

Now you would like to listen to your transmitted wave. But there is a huge problem. Whenever the wave is positive, it causes an upward force on the speaker, and whenever it is negative it causes a downward force on the speaker. The modulated wave is oscillating up and down with the rapid radio frequency, much too fast for the speaker to respond to. It just sits there quivering.

The trick is to add a diode to the output. Remember that a diode is a quantum mechanical component that only allows current to flow in one direction once a turn-on voltage has been reached (determined by the semiconductor band gap energy). This will allow only positive voltage to reach the speaker.



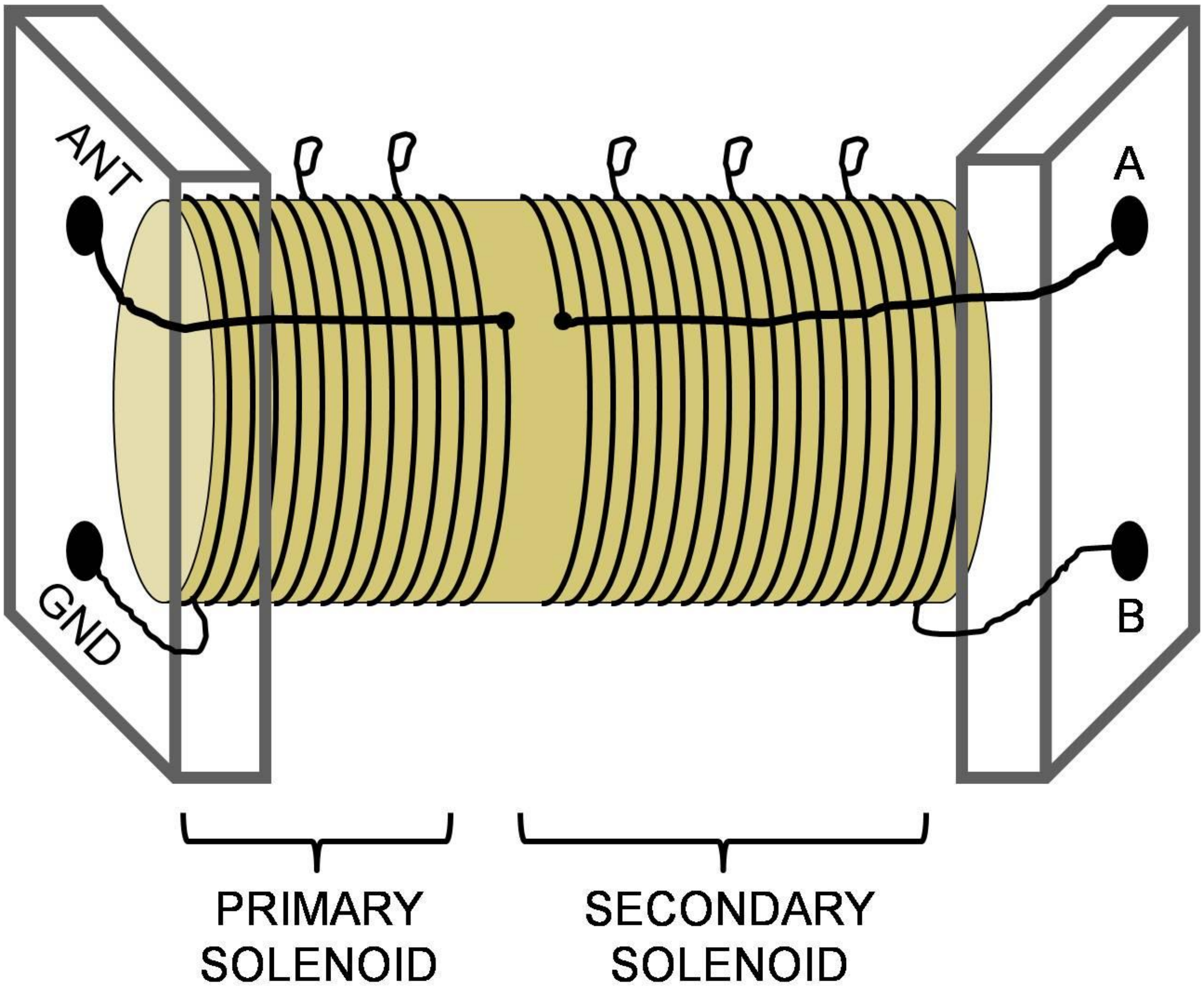
The speaker now gets pushed out a maximum distance at the maximum amplitude of the pulse and relaxes at the minimum.

¿ 1-1

Would you be able to hear the speaker if the direction of the diode in the circuit was reversed? Explain your answer?

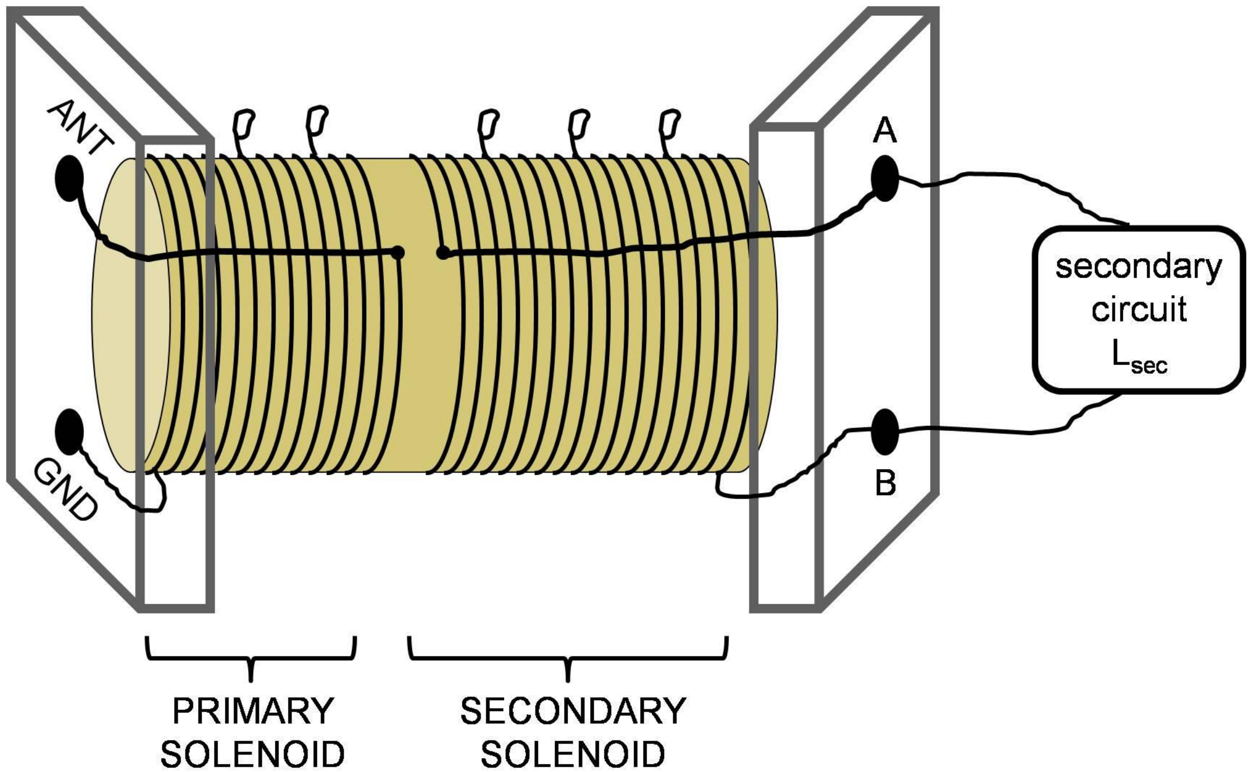
! Never insert the speaker directly into your ear without first verifying that the sound level is safe.

Now you will experimentally use a sound wave to modulate a radio frequency wave.
First examine the equipment with two solenoids:

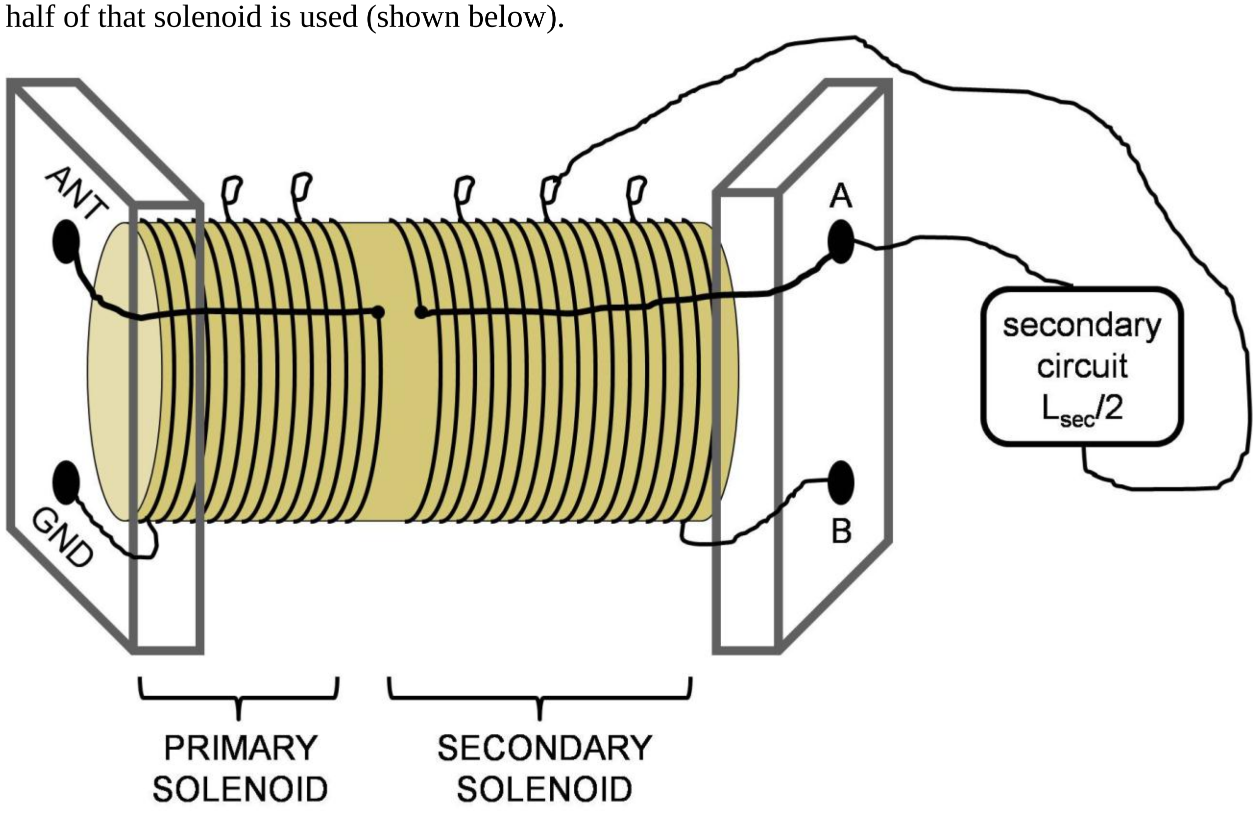


This device allows you to see how two solenoids interact via Faraday's law. There is a small visible gap that separates the two different coils of wire. If you look carefully, you can see that GND connects to the left side of the primary solenoid and ANT connects to the right side of the primary. You can also see that A connects to the left of the secondary and B to the right. In addition to these connections, there are some junctions sticking out of the top of the solenoids. These allow you to use smaller portions of each solenoid if you want less inductance L.

We will always want to use the connections at ANT and A. This forces the current to travel in the parts of the primary and secondary that are adjacent to one another.



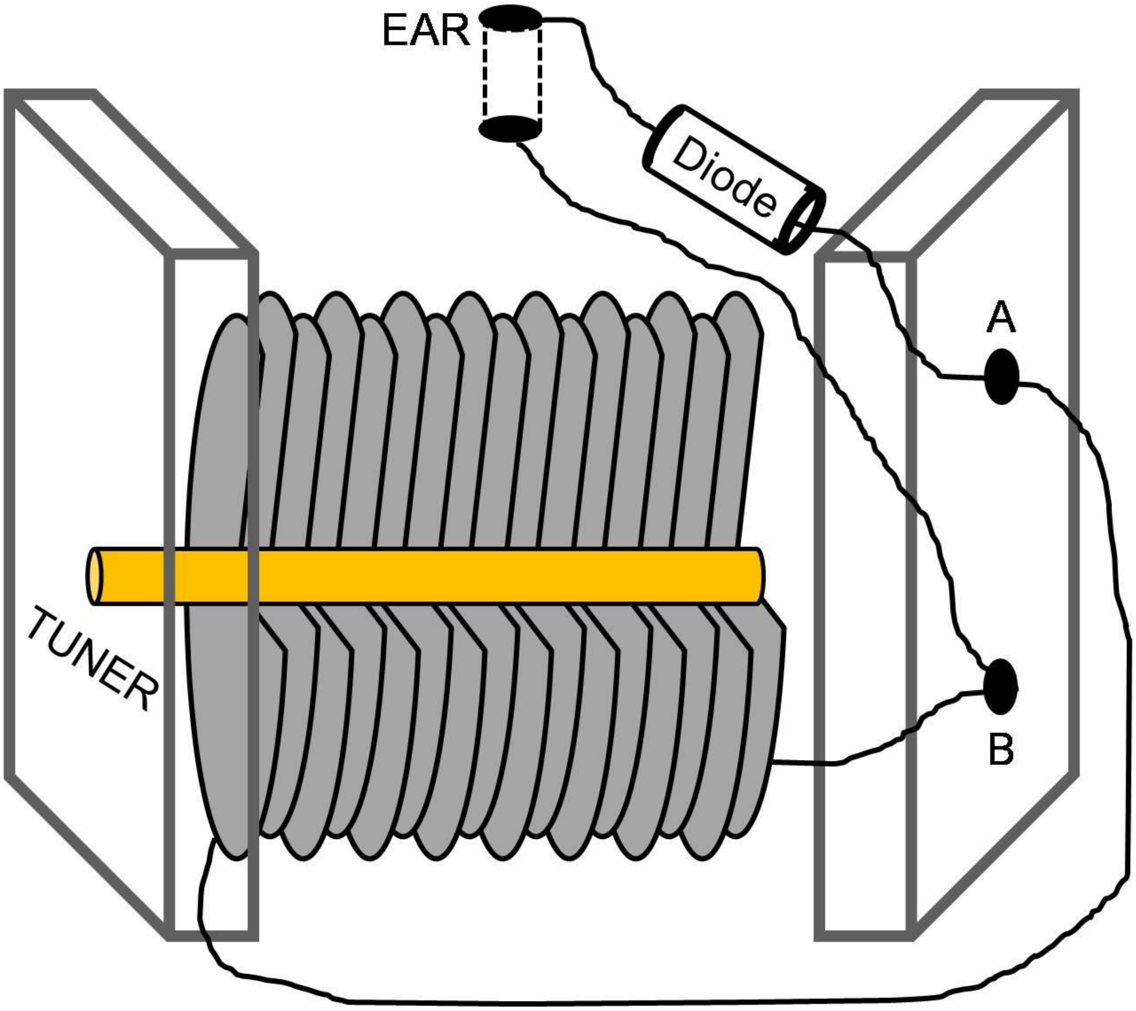
For example, if you wanted to half the inductance of the secondary circuit shown above, you would simply reconnect the B terminal to the midpoint of the secondary solenoid so that only half of that solenoid is used (shown below).



¿ **1-2**

How many possible primary solenoid inductances are possible? How many secondary? {Don't forget that the solenoids must remain immediately adjacent to each other.}

Now examine the equipment with the continuously variable capacitance:



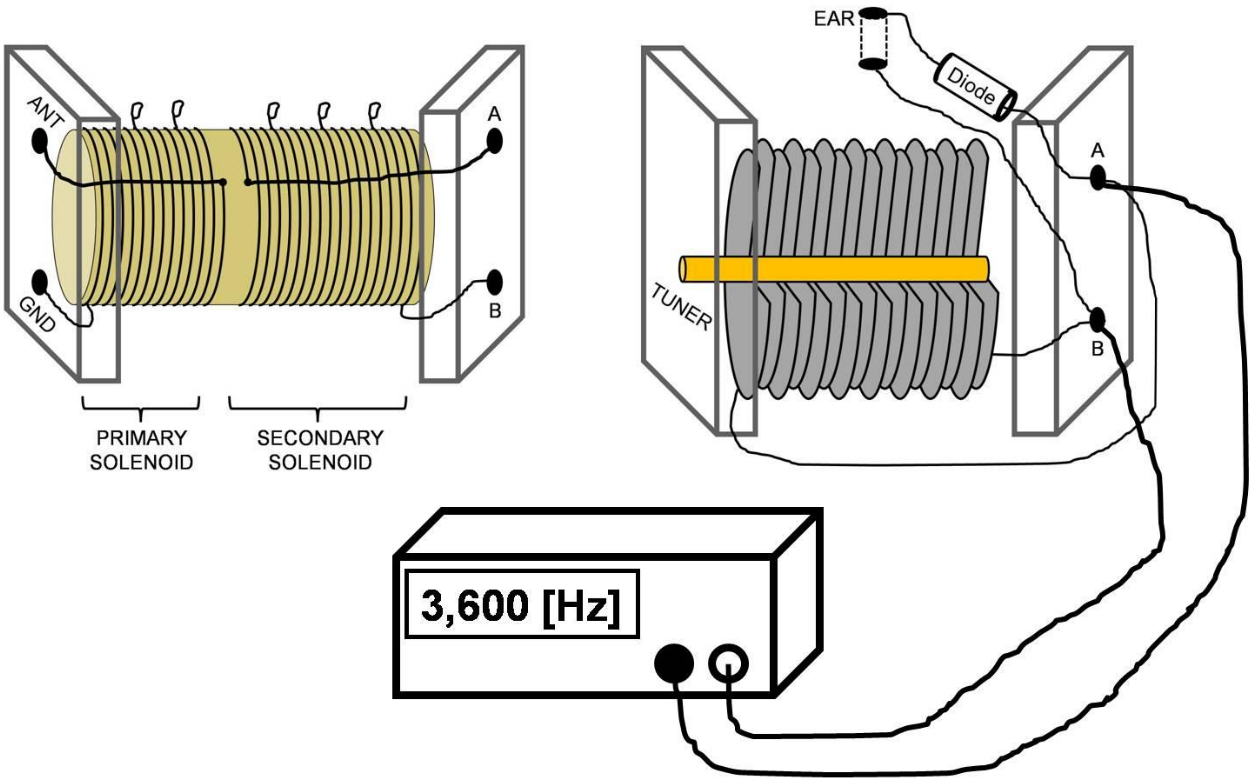
The variable capacitor is made of two sets of overlapping plates. One set can be rotated so that it overlaps more or less with the other set of plates. When they maximally overlap the capacitor has the highest capacitance it can provide. When the plates don't overlap at all, the capacitance is zero.

In addition to the capacitor plates, there is a diode and speaker connector in parallel to the capacitor. Remember that the diode eliminates half the oscillating voltage sent to the speaker.

Now let's be sure you can make the 'sound'. Clean your ear-speaker with alcohol and connect it to the earplug on the capacitor assembly. Set your function generator to 3,600 [Hz]. Connect your function generator to the A and B connections on the variable capacitor assembly as shown below.

Slowly increase the output voltage of the function generator until you can hear the signal.

! **Ask for help if you have any doubts about the proper operation of these devices.**



¿ 1-3

Give yourself a hearing test. Find the upper end of the frequency range of your hearing (or another student if you do not want to test your own hearing). It may be significantly less than your classmates' if you are older or have suffered hearing loss due to loud noises. Also note any intermediate ranges of hearing loss. Do these frequencies correspond to the kinds of music you listen to (too loudly)?

Speakers create sound waves in the air by mechanically oscillating a solid object that strikes air molecules. For a given constant output voltage, cheaper speakers will not respond to all frequencies with the same intensity. Really cheap speakers may even have a few resonant frequencies where they mechanically 'rattle'.

¿ 1-4

Does your simple speaker have any resonant frequencies (probably)? Find and record the frequencies that make the speaker the loudest? There may be more than one resonant frequency for your speaker since it is a complex mechanical system (only very simple systems have one resonant frequency).

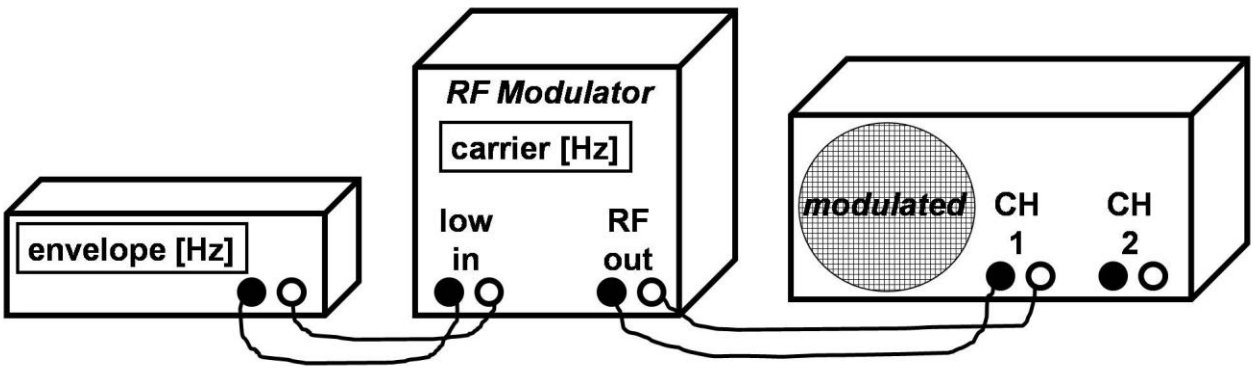
Section 2: the modulated wave

The radio frequency (RF) modulator takes an input envelope wave and modulates it with a rapidly oscillating carrier wave. If you do not input any envelope wave, only the pure carrier wave will be output. Hook your RF modulator directly to the oscilloscope *without* the input envelope wave from the function generator. Use a carrier RF wave of 500,000 [Hz].

¿ 2-1

Use the oscilloscope to determine the period of the 500 [kHz] RF carrier wave. Does this make sense since $T = \frac{1}{f}$**?**

Now input an audio-frequency signal of 1,000 Hz from your function generator into your RF modulator (shown below). Use a carrier radio-frequency wave of 500,000 [Hz] to create a modulated output wave of 1,000 Hz envelope waves surrounding a 500 kHz high frequency wave.



¿ 2-2

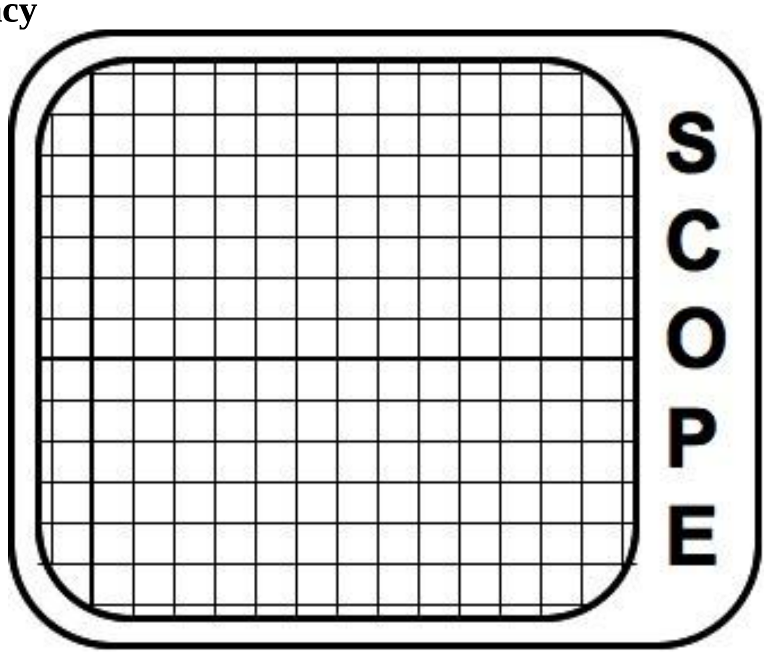
Calculate the period of the envelope wave using $T = \frac{1}{f}$**?**

Examine the output of this signal on your oscilloscope using two different time ranges so that you can see the audio-frequency signal and then separately the radio-frequency signal. To do this, choose a seconds-per-division setting for the time axis that is appropriate for the time scale of the wave you wish to examine (i.e., use the wave's period to select the seconds-per-division). You may need to press the "run-stop" button to view the wave packets if they appear smeared out on the oscilloscope.

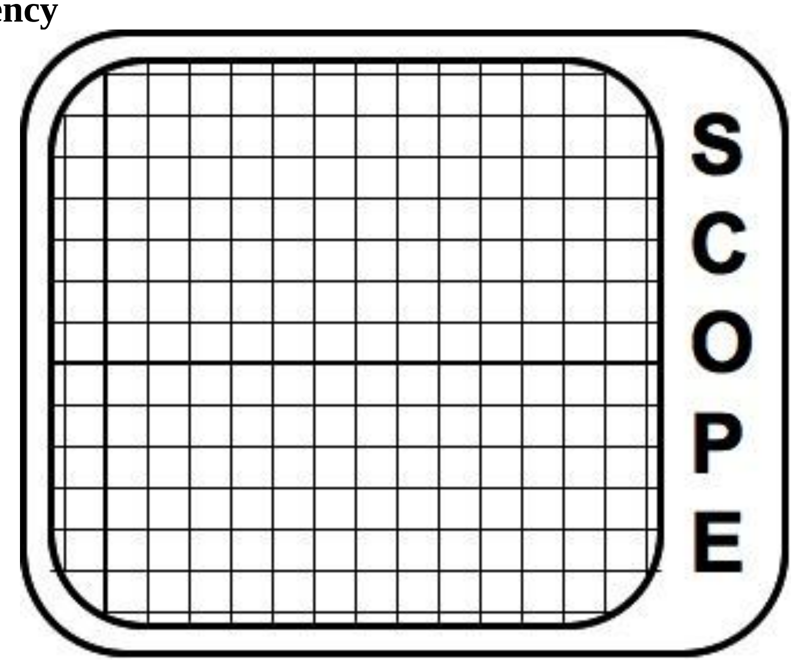
¿ 2-3

Sketch the appearance of the modulated wave at *both* the audio frequency scale and then the radio frequency scale, and record the time scales used to observe the waves. Notice that the RF generator does not necessarily produce a clean RF output as was discussed earlier in this handout. Also, be sure you can hear the envelope waves of the modulated signal in your speaker.

Radio Frequency



Audio Frequency



Section 3: mutual inductance "radio"

Now you will use a sound wave to modulate a radio frequency wave, then use mutual inductance to transmit the radio frequency wave to a separate RLC circuit, and finally listen to the "broadcast" sound wave. Set the capacitor to its maximum setting.

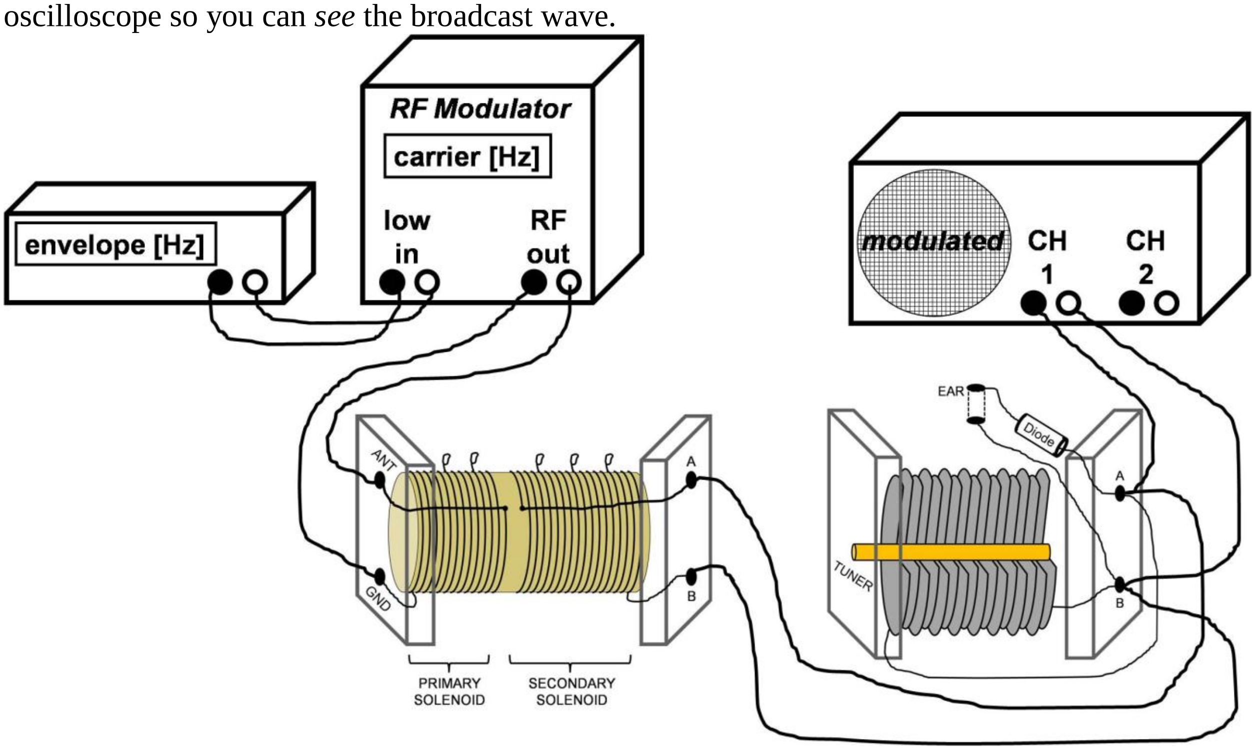
¿ 3-1

First determine the inductances $L_{primary}$ and $L_{secondary}$ of your solenoids using the methods from previous labs. In other words, for each solenoid create an RL circuit driven sinusoidally and monitor the voltage across the resistor and inductor as you vary the driving frequency. Use the appropriate equation to solve for the inductance L. Even with the 10 Ω resistor, you will need to use large driving frequencies as these inductances are very small.

¿ 3-2

Determine the capacitance of the capacitor using methods from a previous lab.

Choose your favorite audio frequency wave to broadcast and a carrier wave initially 550 [kHz]. Instead of trying to hear the broadcast wave in the secondary circuit, send the output to your oscilloscope so you can *see* the broadcast wave.



¿ 3-3

The secondary circuit is supposed to be an RLC circuit with a resonance frequency. Where is the resistance and why would you want the resistance to be as low as possible?

¿ 3-4

Do you expect the secondary circuit to have a resonant frequency nearer to the audio frequency or the carrier frequency?

¿ 3-5

Calculate the resonant frequency $f_{resonance}$ of the secondary circuit.

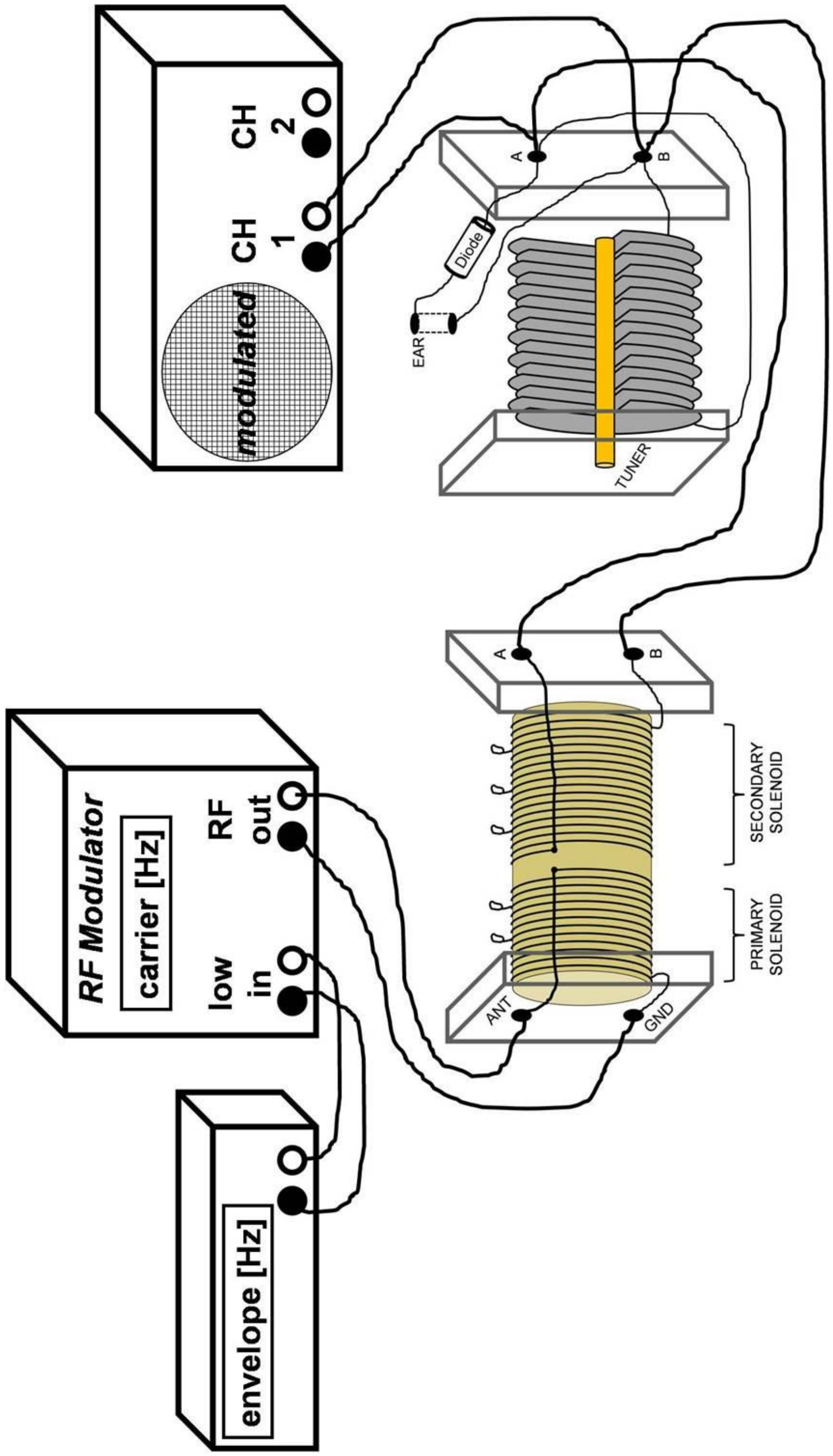
¿ 3-6

Adjust the carrier frequency until a maximum output voltage is determined on the oscilloscope. If it does not match your previous answer, get help. Explain why the carrier wave needs to be at the resonance frequency of the secondary circuit to maximize transmission of the modulated wave.

Now use your earphone to determine that maximum broadcast transmission occurs when the carrier wave is at the resonance of the secondary circuit.

¿ 3-7

Write directly onto the figure below to completely explain how this compound circuit(s) works. You can use labels, text and arrows, and you do not need to write in complete sentences.



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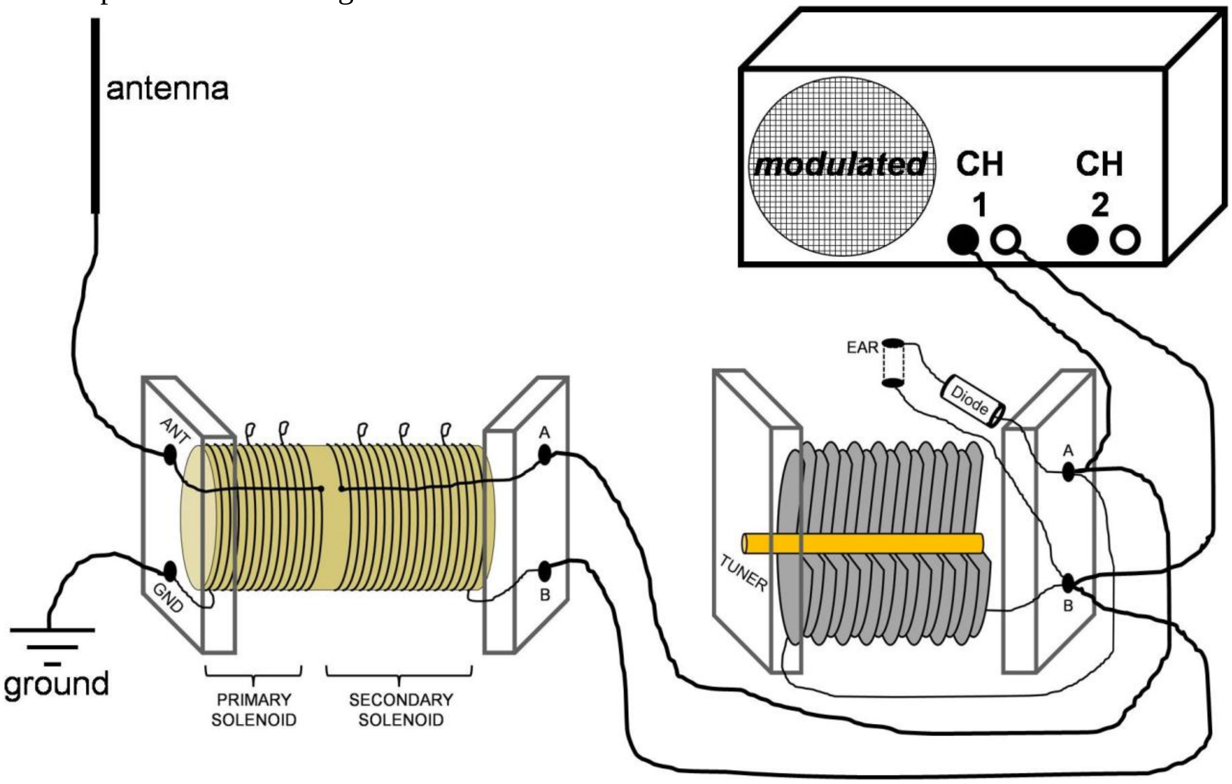
Section 4: authentic assessment - real radio wave reception

Now replace the function generator and RF modulator with a real antenna as shown:



Change the secondary solenoid inductance (4 options) and the capacitance (continuous adjustment) to find radio stations which cause the secondary circuit to have a maximum current (large voltage on the oscilloscope).

If you are uncomfortable having another student check your work, please ask your TA.

¿ 4-1
Record the kinds of stations you find.

"Yes, I have seen this student use an RLC circuit to find invisible sound-carrying light waves. We then rocked out to some jamming tunes!"

Student Signature:____

Section 5: open-ended

Imagine that you are about to finish a very long semester of electricity and magnetism labs, and that all you have left to do is a single open-ended creative design question.

Using two of the large ~1 [H] solenoids stored in the corner of the room, create your own radio station. Specifically, find a way to transmit unmodulated sound waves from one solenoid *through the air* and listen to the sound using a second solenoid not connected in any way to the transmitting solenoid. Decide on what pitch to broadcast using theoretical predictions based on the numerical values of the components you have on hand. Points are awarded for loudness (not really).

At the following prompts, design an experiment to loudly broadcast *unmodulated* sound waves using two large solenoids among other electronics components. Then implement your experiment and record your observations.

You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the following page.

Be sure to read the take home quiz before you leave!

¿ 5-1
hypothesizing/planning:

¿ 5-2
observations/data:

¿ 5-3
calculations/conclusion

Be sure to read the take home quiz right now!

I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: ____**

Week 12 ~~Take-Home Quiz~~

Score:____5___ /5

¿ THQ-1 (5-points)

! If you have finished the lab and have time remaining, you should review lab techniques for the lab practical:

- **Using the DMM to measure:**
  - **voltage**
  - **current**
  - **resistance**
- **Building circuits from schematics:**
  - **series**
  - **parallel**
- **Operation of a DC power supply.**
- **Operation of a function generator:**
  - **square and sin waves**
  - **output frequency**
  - **output voltage amplitude**
  - **DC offset**
- **Oscilloscope general usage:**
  - **middle ground vs bottom ground setups**
  - **time scale**
  - **voltage scale**
  - **where V=0 is on screen**
  - **triggering**
  - **screen capture**
  - **how to get it off French if done so by accident**
- **Oscilloscope measurements (V vs t):**
  - **frequency**
  - **period**
  - **voltage amplitude**
  - **current amplitude (via resistor voltage amplitude)**
- **Oscilloscope measurements (V_x vs V_y):**
  - **RLC resonance**
- **Tricky oscilloscope measurements:**
  - **capacitance**
  - **inductance**

(Repeated) Rules for Excused Absences

You should always email your TA as soon as you know that you will be missing a lab. You are not permitted to attend a different lab than the one for which you are registered. If you have a valid excuse with documentation, then you may complete the Makeup Lab near the end of the semester. Therefore, you may only makeup 1 lab at most.

If you are writing your biweekly lab report and you have been absent 1 week, then you may only earn 75% of the possible lab report points (30) out of the total possible (40). If you have a valid and documented excused absence, completing the makeup lab and writing the report for it will allow you to earn the remaining 10 points for the unit during which you were absent.

When you are writing your biweekly lab report and you have been absent 1 week, then:

- **Write the Mini-Report using the section for which you were present.**
- **Write the Open-Ended Discussion using the open-ended activity for which you were present.**
- **Attach the graphs you created for the week you were present.**
- **Attach the Post-Lab Quiz for the week you were present.**
- **Attach the Selected Worksheet Pages you completed for the week you were present.**

For the makeup lab report, you will need to:

- **Write a Mini-Report.**
- **Do not write an Open-Ended.**
- **Attach the graphs you create for the makeup lab.**
- **There is no Take-Home Quiz for the makeup lab.**
- **Attach the *all* the Worksheet Pages you completed for the makeup lab.**

Makeup Lab Report Instructions

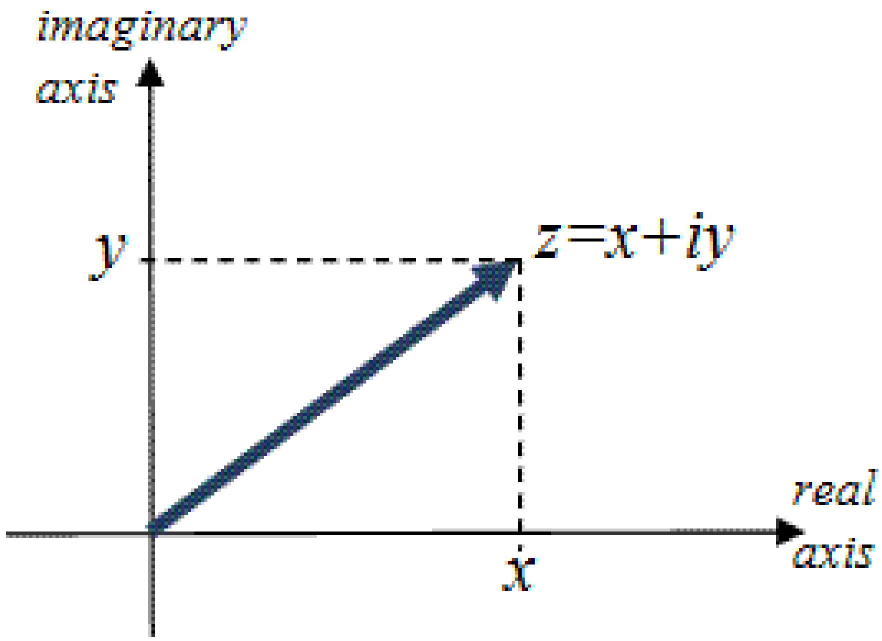
Unit Lab Report [10 points toward the unit during which you were absent]

Use the following section titles in your report. Images, text or equations plagiarized from the internet are not allowed! Remember to write your report *alone* as collaborating with a lab partner will make you both guilty of plagiarism. **Please label your makeup lab report sections:**

- **Title [0 points]** – A catchy title worth zero points so make it unique and fun.
- **Mini-Report [3 points]:** ***{4-5 paragraphs, ~2 double-spaced pages}***
  Choose **one** of the following sections about which to write your mini-report:
  Makeup Lab Section 3
  Write a "mini-report" for one particular section of the lab manual. Describe what you did succinctly, and then what you found accurately. Then explain what the result means and how it relates to some of the concepts in the previous section. *You must write using sentences & paragraphs; bulleted lists are unacceptable.* ***Please label your mini-report sections.***
  - **Abstract:** Write 2-3 sentences about the goals of this section. Describe the concepts you were investigating and how the experimentation you performed allowed you to investigate these concepts. Write 2-3 sentences summarizing the procedure. Write 2-3 sentences summarizing the results and what the results mean with regard to the concepts you were investigating. *It is best to write the abstract last*.
  - **Procedure:** Do not provide a lot of specific details, but rather you should summarize the procedure so that a student who took the course a few years ago would understand what you did.
  - **Results:** Provide a description of the data you obtained such as data tables. Restate any measured values, calculated slopes of lines-of-best-fit, etc. Do not *interpret* your results, save any interpretation for the discussion.
  - **Discussion:** Analyze and interpret the results you observed/measured in terms of some of the concepts and equations of this unit. It is all right to sound repetitive with other parts of the report.
- **Do not write an open-ended discussion.**
- **Graphs [1 point] - {attach to your typed report}** Graphs must be neatly hand-drawn <u>during lab</u> on graph paper. Your graphs must fill the entire page (requires planning ahead), include a descriptive title, labeled axes, numeric tic marks on the axes, and unit labels on the axes. If instructed to calculate the slope of the line-of-best-fit, write it directly on the graph.
  Makeup lab: 2-3
- **There is no take-home quiz.**
- **Selected Worksheet Pages [1 point] - {attach after your graph }**
  Hand in *all* your makeup lab worksheet pages.

Makeup Pre-Lab: RLC Circuit using Phasors

Phasors are vectors in the complex plane used to represent real-valued quantities that oscillate in time (like voltages in an AC circuit). Since a complex number has a real and imaginary part, z=x + *i*y, a complex number can also be thought of as a vector in the complex plane:



A complex number can also be expressed in polar form $z = re^{i\theta}$ where r is the radial distance from the origin $r = \sqrt{x^2 + y^2}$ and θ is the phase angle from the real axis $\tan^{-1}(y/x)$. Euler's formula relates the complex polar form to the geometry of the phasor:

$$re^{i\theta} = r\cos(\theta) + ir\sin(\theta).$$

When applied to a phasor, Euler's formula shows that if we use the complex number system to describe a real system, we can recover the real values by keeping the real term and ignoring the imaginary term:

$$\text{Real}\{re^{i\theta}\} = r\cos(\theta).$$

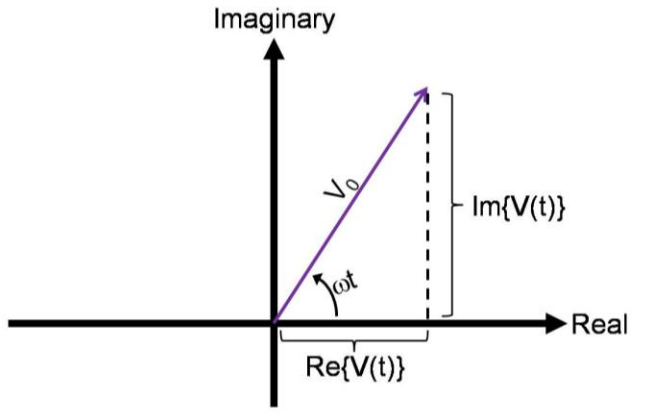
The concept of phasors can be applied to voltages in a sinusoidally driven RLC circuit:

$$V(t) = V_0 e^{i\omega t}$$

where if you need the actual value of the voltage at any time you must use the real part:

$$\text{Real}\{V(t)\} = V_0 \cos(\omega t).$$

Phasors are not stationary when describing time-dependent quantities. Because phasors are functions of time, they rotate around in the complex plan:

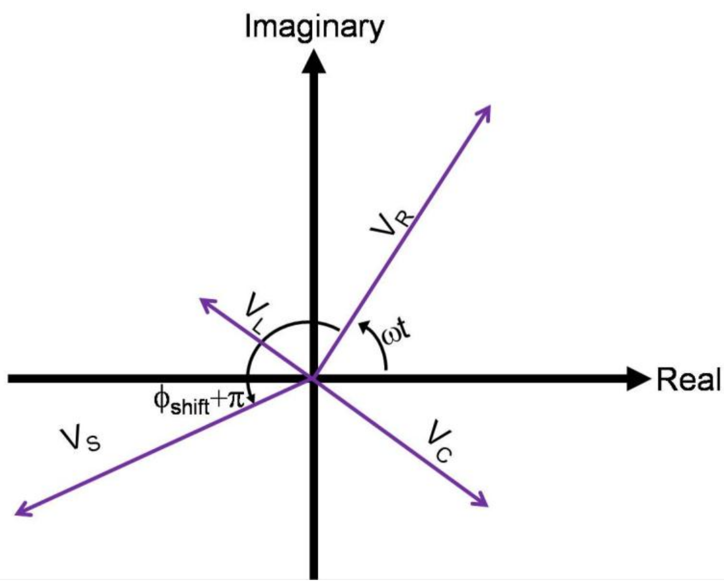


$V(t)=V_0e^{i\omega t}$ rotates around the complex plane in time.

Note that the real value of the voltage is the projection of the phasor onto the real axis (using the cosine of the angle), and this real voltage changes in time as the phasor rotates. That is good since we want the real part of the phasor to describe a sinusoidally oscillating voltage: $\text{Real}\{V(t)\}=V_0\cos(\omega t)$. Each of the component voltages in a sinusoidally driven RLC circuit may be described with phasors:

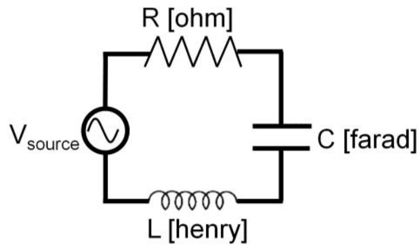
$$V(t)_{\text{source}}=V_{\substack{\text{source}\\\text{amplitude}}}\,e^{(\omega_{\text{drive}}t+\phi_{\text{shift}}+\pi)i}\qquad V(t)_{\text{resistor}}=V_{\substack{\text{resistor}\\\text{amplitude}}}\,e^{(\omega_{\text{drive}}t)i}$$

$$V(t)_{\text{capacitor}}=V_{\substack{\text{capacitor}\\\text{amplitude}}}\,e^{\left(\omega_{\text{drive}}t-\frac{\pi}{2}\right)i}\qquad V(t)_{\text{inductor}}=V_{\substack{\text{inductor}\\\text{amplitude}}}\,e^{\left(\omega_{\text{drive}}t+\frac{\pi}{2}\right)i}$$



Note that adding the complex phasors is equivalent to adding all the voltages of the circuit. The sum must equal zero. ϕ_{shift} is negative in the above example.

Pre-Lab Practice Questions



A sinusoidally driven RLC circuit has a frequency of $f = 1{,}100\,[\text{Hz}]$ **or** $\omega = 2\pi f = 6912\left[\frac{1}{\text{s}}\right]$ **and a source voltage amplitude of** $V_{\text{source},0} = 10\,[\text{V}]$**. The components are chosen so that at this frequency** $R = 3\ [\Omega]$**,** $\chi_C = 10\ [\Omega]$**,** $\chi_L = 6\ [\Omega]$ **and thus** $Z = \sqrt{R^2 + (\chi_L - \chi_C)^2} = 5\,[\Omega]$**.**

This gives $V_{\text{R},0} = \frac{R}{Z} V_{\substack{\text{source}\\\text{amplitude}}} = 6\,[\text{V}]$**,** $V_{\text{C},0} = \frac{\chi_C}{Z} V_{\substack{\text{source}\\\text{amplitude}}} = 20\,[\text{V}]$**, and** $V_{\text{L},0} = \frac{\chi_L}{Z} V_{\substack{\text{source}\\\text{amplitude}}} = 12\,[\text{V}]$**.**

It also indicates that $\phi_{\text{shift}} = \arctan\left(\frac{\chi_L - \chi_C}{R}\right) = -0.93\,\text{radians} = -53.1^o$**.**

Thus $V(t)_{\text{source}} = 10e^{(6912t - 0.93 + \pi)i}\ [\text{V}]$ $\qquad V(t)_{\text{resistor}} = 6e^{(6912t)i}\ [\text{V}]$

$$V(t)_{\text{capacitor}} = 20e^{\left(6912t - \frac{\pi}{2}\right)i}\ [\text{V}] \qquad V(t)_{\text{inductor}} = 20e^{\left(6912t + \frac{\pi}{2}\right)i}\ [\text{V}]$$

Decompose each of the four circuit voltages into real and imaginary components for t=0 [s]. Then check that the sum of the real parts equals zero, and separately the sum of the imaginary parts sum to zero, so that conservation of energy is assured.

Check: You should find that:

$$V(0)_{\text{source}} = -6\,[\text{V}] + i \cdot 8\ [\text{V}]$$
$$V(0)_{\text{resistor}} = +6\,[\text{V}] + i \cdot 0\ [\text{V}]$$
$$V(0)_{\text{capacitor}} = 0\,[\text{V}] - i \cdot 20\,[\text{V}]$$
$$V(t)_{\text{inductor}} = 0\,[\text{V}] + i \cdot 12\ [\text{V}]$$

Added together gives:

$$V(0)_{\text{total}} = 0\,[\text{V}] + i \cdot 0\ [\text{V}]$$

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Makeup Lab: RLC Circuit using Phasors

Students Absolutely Must Learn…

- Understand complex numbers written in polar form versus Cartesian form.
- Understand how the real component of a complex number can describe real voltages.
- How to use phasors for V_R, V_C and V_L to predict the magnitude and phase shift of the source voltage.
- Advanced oscilloscope techniques.

Section 1: review sinusoidally driven RLC circuits

In a circuit where an inductor, resistor and capacitor (RLC) are connected in series and driven by a sinusoidal (AC) source, the voltage across each of the components varies with time reaching a maximum and a minimum at regular intervals. The properties of the RC circuit and RL circuit studied previously combine in a straightforward manner. Combining the results obtained in previous labs we can measure the voltage across each component with respect to time as done below:

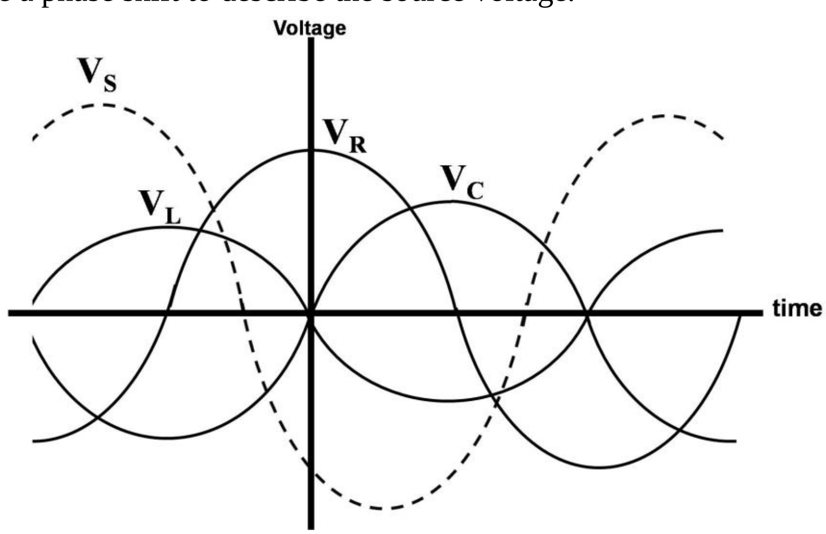
$$V(t)_{\text{resistor}} = R \cdot I_{\text{amplitude}} \cos(\omega_{\text{drive}} t) \qquad V(t)_{\text{source}} = V_{\substack{\text{source}\\\text{amplitude}}} \cos(\omega_{\text{drive}} t + \phi_{\text{source}} + \pi)$$

$$V(t)_{\text{capacitor}} = \chi_C \cdot I_{\text{amplitude}} \cos\left(\omega_{\text{drive}} t - \frac{\pi}{2}\right) \qquad V(t)_{\text{inductor}} = \chi_L \cdot I_{\text{amplitude}} \cos\left(\omega_{\text{drive}} t + \frac{\pi}{2}\right)$$

where, $I_{\text{amplitude}} = \dfrac{V_{\text{source amplitude}}}{Z}$, $\quad Z = \sqrt{R^2 + (\chi_L - \chi_C)^2}$, $\quad \chi_C = \dfrac{1}{\omega_{\text{drive}} C}$, $\quad \chi_L = \omega_{\text{drive}} L$,

$\phi_{\text{source}} = \tan^{-1}\left(\dfrac{\chi_L - \chi_C}{R}\right)$.

The above equations show that the capacitor voltage lags behind the resistor voltage by 90^o while the inductor voltage leads the resistor voltage by 90^o. Note that in the above equations we take the resistor as the reference point because it is Ohmic and thus also describes the circuit current, hence we must use a phase shift to describe the source voltage.



¿ 1-1

If R = 20 [Ω], L = 15 [H], C = 10 [F], $V_{\text{source amplitude}}$ = 10 [V] and f_{drive} = 50 [Hz], find the voltage amplitudes of the inductor and capacitor (in SI units).

¿ 1-2

Use the following values to calculate each of the RLC circuit parameters below: $V_{\text{source amplitude}}$= 5 [V], f_{drive}= 700 [Hz], R= 1000 [Ω], C = 10 [μF], L = 100 [mH]. Write the numerical value with correct SI unit for each listed parameter:

χ_C= χ_L= Z=

$V_{R,\text{amplitude}}$= $V_{C,\text{amplitude}}$= $V_{L,\text{amplitude}}$=

ϕ_{source}= $I_{\text{amplitude}}$=

Section 2: practice calculating phasors

Use the following values in the following questions:
$V_{source\ amplitude}$= 5 [V], f_{drive}= 700 [Hz], R= 1000 [Ω], C = 10 [μF], L = 100 [mH].

¿ 2-1
Calculate the time dependent phasors and write them in complex exponential notation for each of the four voltages of the RLC circuit.

¿ 2-2
Compute the real and imaginary components of each of the four voltage phasors at t=10 [ms] and make sure both the real and the imaginary components sum to zero.

¿ 2-3

On graph paper, plot your four voltage phasors at t=0 on the complex plane. Be sure to label magnitudes and phase shifts for each of the phasors. (Your graph must be planned ahead to fill the entire page, have labeled and hash-marked axes and a descriptive title.)

¿ 2-4

Calculate and write the time dependent current as a complex exponential phasor.

Section 3: measuring the phasors

Construct a sinusoidally driven RLC circuit using the following values:
$V_{\text{source amplitude}}$= 5 [V], f_{drive}= 700 [Hz], R= 1000 [Ω], C = 10 [μF], L = 100 [mH].

¿ 3-1
Measure the voltage amplitudes of each of the four circuit component voltages and compare these to your calculations in the previous section. The measured values should be approximately equal to your calculated values.

¿ 3-2
Measure the time shift t_{shift} between the source voltage and resistor voltage and use this to calculate the measured phase shift. Remember that

$\phi_{\text{source}} = \dfrac{2\pi \cdot t_{\text{shift}}}{T} - \pi = \omega_{\text{drive}} \cdot t_{\text{shift}} - \pi$ **.**

Section 4: authentic assessment

Perhaps the most critical feature of a sinusoidally driven RLC circuit is the fact that there exists a resonant frequency at which the circuit's current amplitude is maximized (or alternatively, when the circuit's total impedence Z is minimized).

! **For the following circuit parameters, $V_{\text{source amplitude}}$= 5 [V], R= 1000 [Ω], C = 10 [µF], and L = 100 [mH], use the oscilloscope in XY mode measuring the voltages of the correct two components to find the resonant frequency. Be sure to use the fact that theoretically $\omega_{\text{resonance}} = \frac{1}{\sqrt{LC}}$ to check your work.**

If you are uncomfortable having another student check your work, please ask your TA.

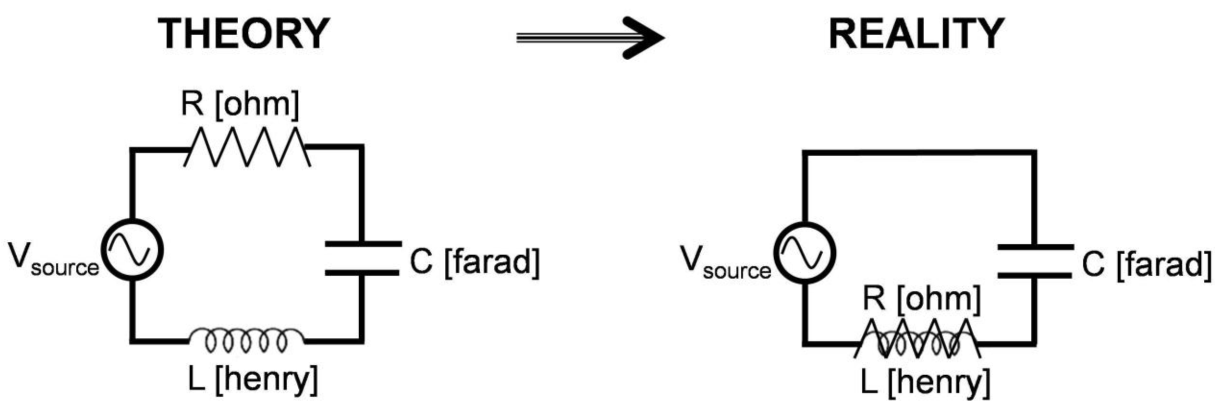
¿ 4-1

Show a student in a different group that you can successfully measure the resonance frequency of an RLC circuit (four circuits, compare your data with theirs). Once you are successful, have them sign below. Note: if someone is stuck, please give them advice!

"Yes, I have seen this student successfully the resonance frequencies of four RLC circuits. Their results match mine. Either they are doing it right or we are both wrong in the same way!"

Student Signature:____

Section 5: open-ended / creative design



In real life, we often deal with non-ideal circuit components. For this open-ended, you will investigate a non-ideal solenoid. If the solenoid is made from a very long wire, it can have a sizeable resistance. This means that the oscilloscope when measuring the voltage across the inductor is composed of two components: $V_{\substack{\text{real}\\\text{inductor}}}(t) = V_{\substack{\text{ideal}\\\text{inductor}}}(t) + V_{\substack{\text{ideal}\\\text{resistor}}}(t)$. But these two components are mixed together so that the oscilloscope is unable to separate them!

Use a 5.555 [μF] capacitor (using the capacitor box) in series with a large unknown solenoid (sinusoidally driven) and the concept of phasors to devise a method to find $V_{\substack{\text{ideal}\\\text{inductor}}}(t)$ and $V_{\substack{\text{ideal}\\\text{resistor}}}(t)$, the two ideal components for the very real solenoid.

You are allowed to "cheat" by talking to other groups for ideas, but are not allowed to "cheat" by just stating an answer you may already know, looking it up online or asking your TA.

Below you are given three prompts: **hypothesizing/planning, observations/data, calculations/conclusion.** Your job is to figure out the answer using these prompts as your problem-solving model. In the event that you should run out of time, you may not discover the correct answer, but you should make an attempt at each prompt. Grades are based on honest effort.

Your open-ended solution should probably include some of the following items: sketches of circuit diagrams, tables of data, calculations, recorded observations, random ideas, etc.

Write at the prompts on the next page.

¿ **5-1**
hypothesizing/planning:

¿ **5-2**
observations/data:

¿ **5-3**
calculations/conclusion

I, the physics 241 laboratory TA, have examined this student's Weekly Activity pages and found them to be thoroughly completed.

! **TA signature: ____**

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Appendix

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Assessment: Learning Outcomes

Introductory electricity & magnetism laboratory students should be prepared for leadership roles in an increasingly diverse, technological and highly competitive world. To this end, these students should…

- Understand the role of science in our society.
    - There is electronic circuitry all around us in the walls of our buildings, in the gadgets we carry, in our transportation & communication, in life-saving medical equipment, and even within our own bodies.
    - How charges flow through metals freely or become deposited on objects is the basis for the majority of our technology. An elementary understanding of charge separation is essential for modern chemistry and biology and many other fields.
    - How charged conductors produce electric fields or equivalently how they produce electric potential landscapes helps students understand how the electric field actually permeates the space we live in.
    - How charged plates can accelerate and steer moving charges, a concept widely used in older technologies.
    - How Ohm's law allows one to quickly unravel the nature of common circuitry that live in our gadgets and machines.
    - How the quantum mechanics of semiconductors has given us personal electronics and high-speed computing.
    - How a capacitor can store energy for later use in an electric field.
    - How a sinusoidal alternating current works to power circuit components and causes sinusoidal responses in the components of the circuit.
    - How motors function, how they are designed, and how to measure their properties.
    - How a solenoid affects an AC circuit allowing electrical energy to be stored in a magnetic field.
    - The resonance behavior of an RLC circuit that allows devices to be tuned to specific frequencies.
    - The mutual inductance of transformers that carry energy across the world.

- Have a firm grasp of the theories that form the basis of electricity and magnetism.
    - Use Gauss's Law to understand electric potential in circuits as conservation of energy.
    - Use Gauss's Law to understand how charges are transported in physical systems.
    - Relating a stationary vector field to its corresponding scalar potential field.
    - Relating voltage differences to electric fields, forces and accelerations of charged particles.
    - Using Ohm's Law to predict total circuit properties and individual component properties.
    - Experimentally testing Ohm's law to solidify conceptual understanding and to be exposed to the interplay of electricity & magnetism and quantum mechanics.

- Use differential equations and their solutions to model and understand circuit behavior.
    - Use differential equations and their solutions to model and understand circuit behavior.
    - Use concepts of magnetism to understand motors.
    - Use of Faraday's Law, Ampere's Law and Lenz's Law.
    - Use trigonometric functions to model a complex circuit.
    - Use of Faraday's law.

- Be able to apply the principles of physics to solve real world problems.
    - Design an experiment to find how resistance adds in series vs. parallel.
    - Design an experiment to find how macroscopic charge separation works on a large conductor.
    - Design an experiment to find how a cathode ray conductor produces an electric field that may accelerate charged particles.
    - Design an experiment to probe the hidden structure of a cathode ray tube.
    - Design an experiment to analyze the microscopic electrical properties of an unknown material.
    - Design an experiment to analyze the microscopic electronic properties of an unknown device.
    - Design an experiment to analyze the behavior of compound capacitors.
    - Design an experiment to build and measure a homemade capacitor.
    - Build a working motor and design an experiment to analyze its behavior.
    - Design an experiment to maximize mutual inductance.
    - Design an experiment to determine the anti-resonant behavior of an multiple-component circuit.
    - Transmit and detect sound ways through the air (using radio waves). Also to detect ambient electromagnetic radiation and determine its frequency.

- Be familiar with basic laboratory equipment, and should be able to design and carry out experiments to answer questions or to demonstrate principles.
    - Skills developed throughout lab especially the open-ended component.
    - Use of DMM, electroscope, Faraday ice pale, wires with various types of leads, resistors, capacitors, inductors/solenoids, modern digital oscilloscopes, function generators, RF modulators, antennae, motors, and magnets/compasses.

- Be able to communicate their results through written reports.
    - Throughout the semester, students write six biweekly unit-themed lab reports using general and specific writing guidelines. Though a revision/editing process is untenable, students will be given their first graded report in advance of the due date of their second report so they can learn from mistakes, discuss alternate writing strategies with the TA, etc.

Graduates of the introductory electricity & magnetism laboratory should…

- Have a broad education that will allow them to succeed in diverse fields such as business, law, medicine, science, writing, etc.
    - Writing skills, critical thinking skills, creative problem-solving skills, communicating ideas & information, teamwork skills, leadership skills, working with time constraints.

- Have mastered the introductory theoretical techniques and electricity and magnetism experimental techniques that are commonly expected for students at this level. Across the world, all introductory electricity and magnetism students must be able to:
    - Apply Gauss's Law to find the electric field. Wire circuit components in series and parallel. Use a DMM to measure current, voltage & resistance. Reason about global circuit properties based upon the arrangement of the components.
    - Understand polarization, use the process of induction, use an electrometer and Faraday ice pail, and calculate the attractive electrostatic force caused by polarization.
    - Understand how an energy landscape produces forces or equivalently how an electric potential landscape produces electric fields and use voltage measurements to calculate an electric field.
    - Calculate how voltages accelerate charged particles and carry out a long and complex mathematical derivation.
    - Understand how to analyze a circuit built from Ohmic components and build Ohmic circuits and measure their properties.
    - Use an oscilloscope to measure rapidly changing voltages, build circuits and measure their properties.
    - Use a digital oscilloscope to investigate RC circuits driven with square waves and sinusoidal waves.
    - Use a digital oscilloscope to investigate RL circuits driven with sinusoidal waves.
    - Use a digital oscilloscope to investigate RLC circuits and radio transmission principles.
    - Design simple radios.

- Be familiar with the principles and practice of engineering and should be able to apply their knowledge to solve state of the art problems, both individually and as part of a team.
    - Individuals must be able to
        - Make a light bulb work.
        - Use a compass to label the poles of a magnet.
        - Measure voltage to find an electric field.
        - Predict the behavior of moving charges in a magnetic field.
        - Build and test simple circuits.
        - Build a working motor.
        - Build a resonating circuit to detect ambient radio waves.
    - Teams must devise an experiment to
        - Measure the equivalent resistance of parallel components.

- Measure the macroscopic charge separation across a large conductor in the presence of an electric field.
- Determine the acceleration on a charged particle by the electric field produced by charged cathode ray plates.
- Determine the hidden arrangement of conducting plates in a cathode ray tube.
- Determine the resistivity of Nichrome wire.
- Determine if a grain-of-wheat bulb is Ohmic.
- Determine the behaviors of multiple capacitors.
- Build and measure a capacitor.
- Measure the properties of a motor.
- Maximize mutual inductance.
- Discover the anti-resonance of a parallel RLC circuit.
- Broadcast sound waves through the air to a receiver.

Other